Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

NOvA Update

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Fermilab PAC

20 June 2016

In partnership with:

NOvA

NOvA Collaboration

- 180 Physicists – Faculty, Scientists, Post-docs, and Students
- 41 Institutions in 7 Countries

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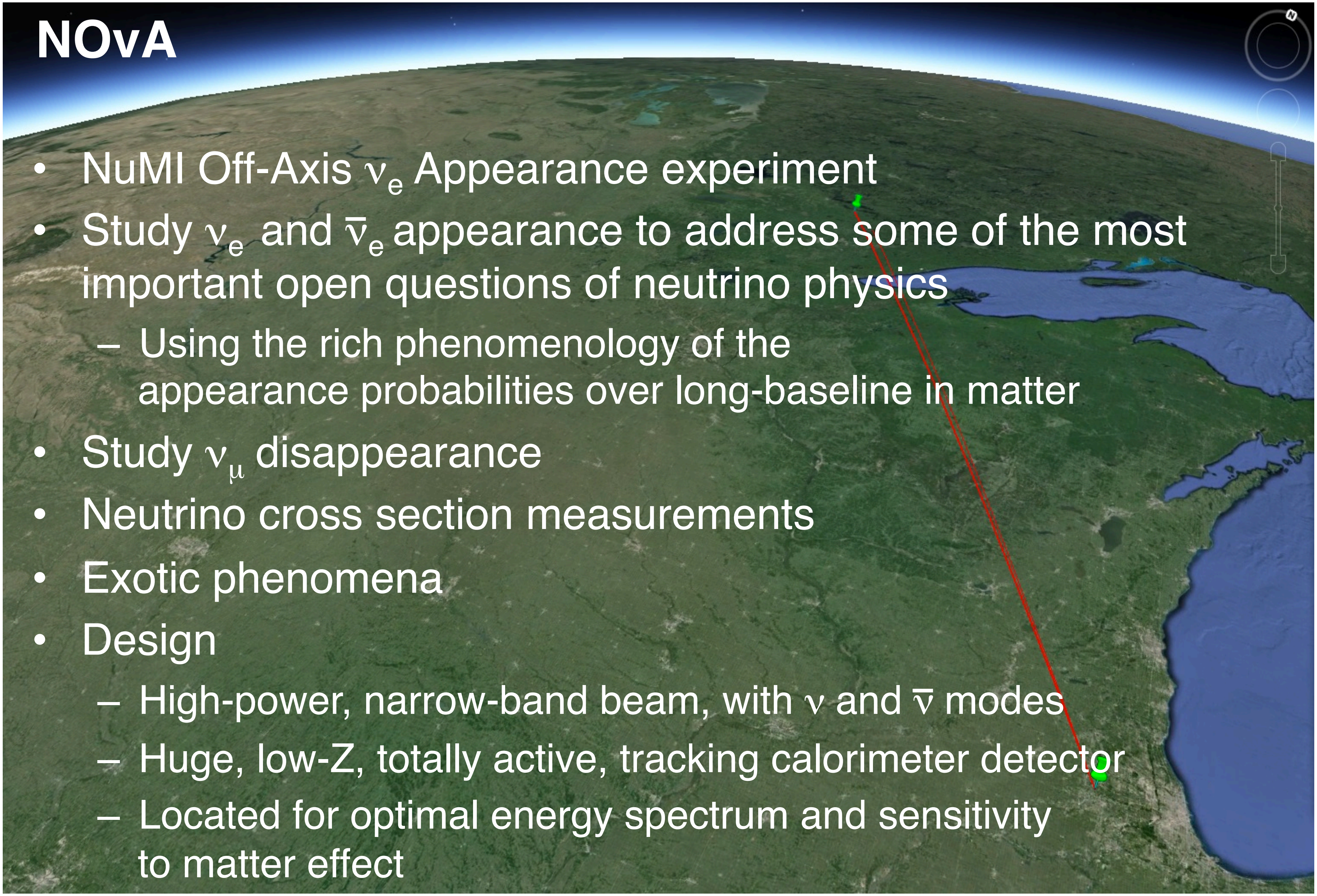
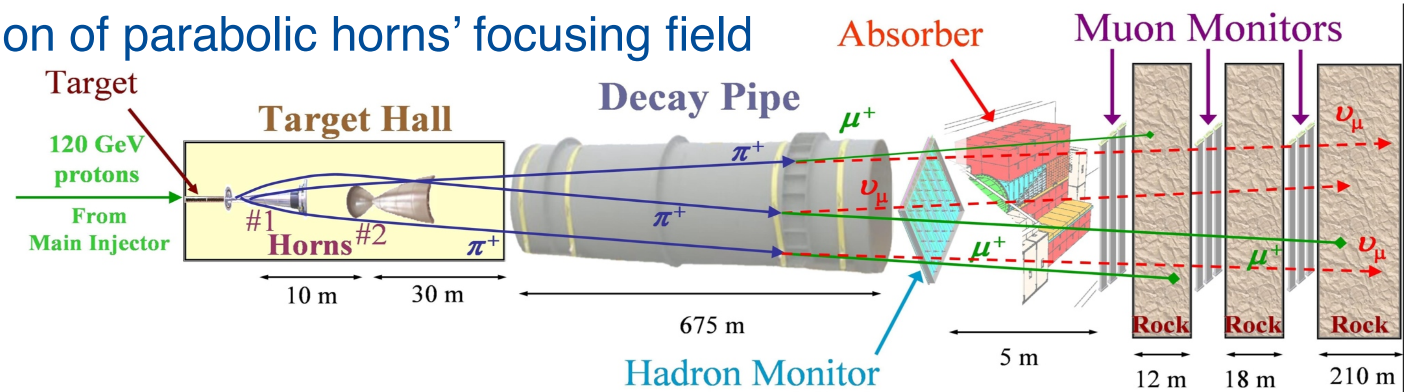
NOvA

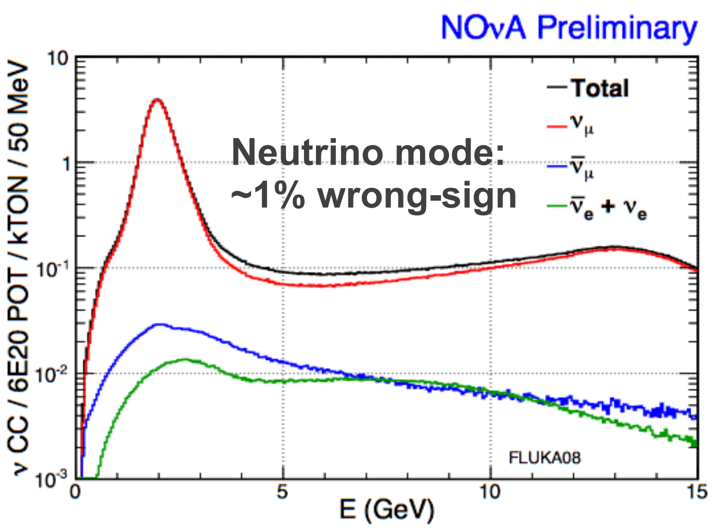


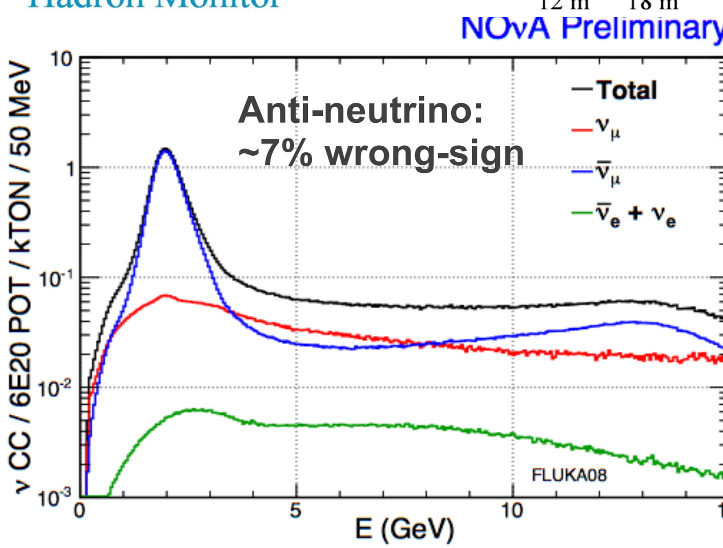
- NuMI Off-Axis ν_e Appearance experiment
- Study ν_e and $\bar{\nu}_e$ appearance to address some of the most important open questions of neutrino physics
  - Using the rich phenomenology of the appearance probabilities over long-baseline in matter
- Study ν_μ disappearance
- Neutrino cross section measurements
- Exotic phenomena
- Design
  - High-power, narrow-band beam, with ν and $\bar{\nu}$ modes
  - Huge, low-Z, totally active, tracking calorimeter detector
  - Located for optimal energy spectrum and sensitivity to matter effect

NuMI Beam

- High beam power – 700 kW design
  - NuMI/accelerator upgrade was a major part of the NOvA project
- ν and $\bar{\nu}$ beam modes
  - Direction of parabolic horns' focusing field

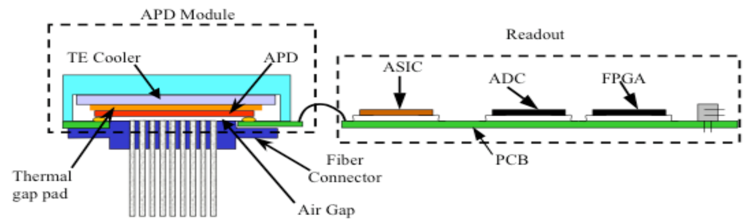


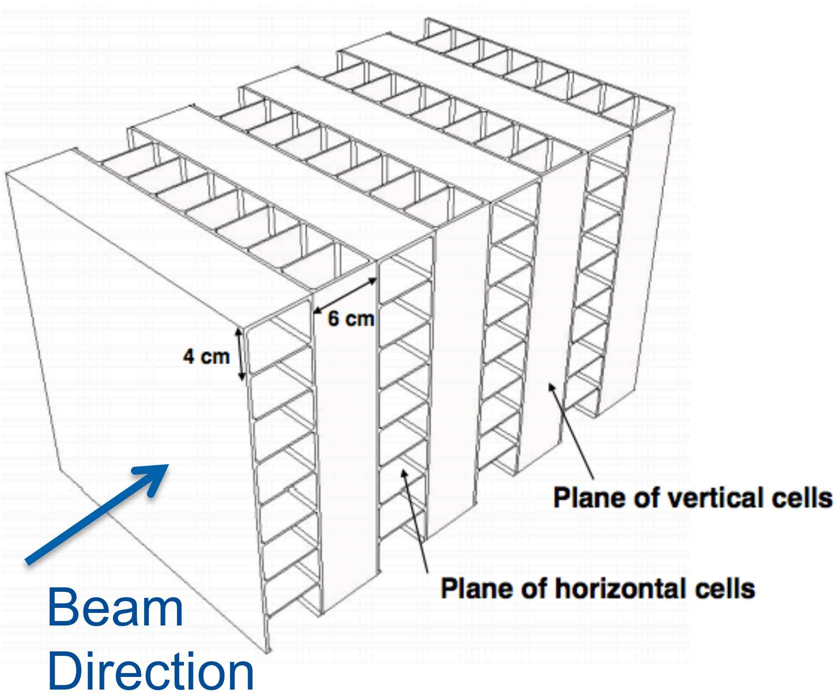




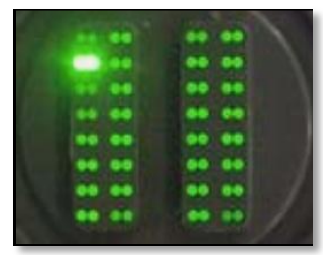
NOvA Detector Technology

- Low-Z tracking Calorimeter
  - PVC Cell Structure
  - Mineral oil + 5% pseudocumene

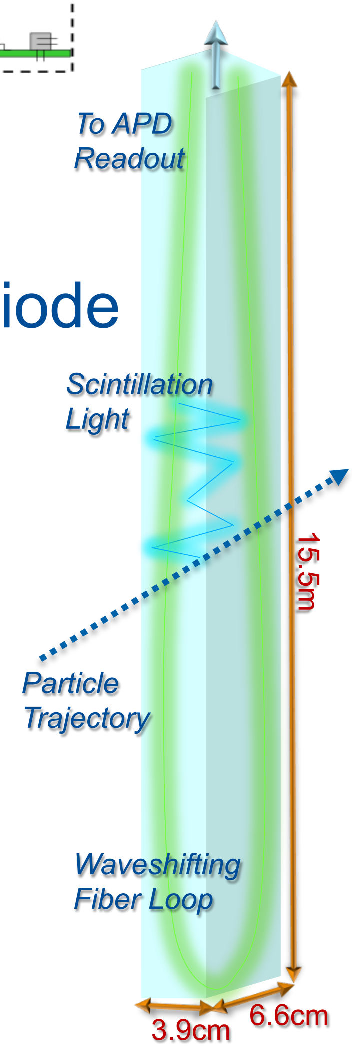




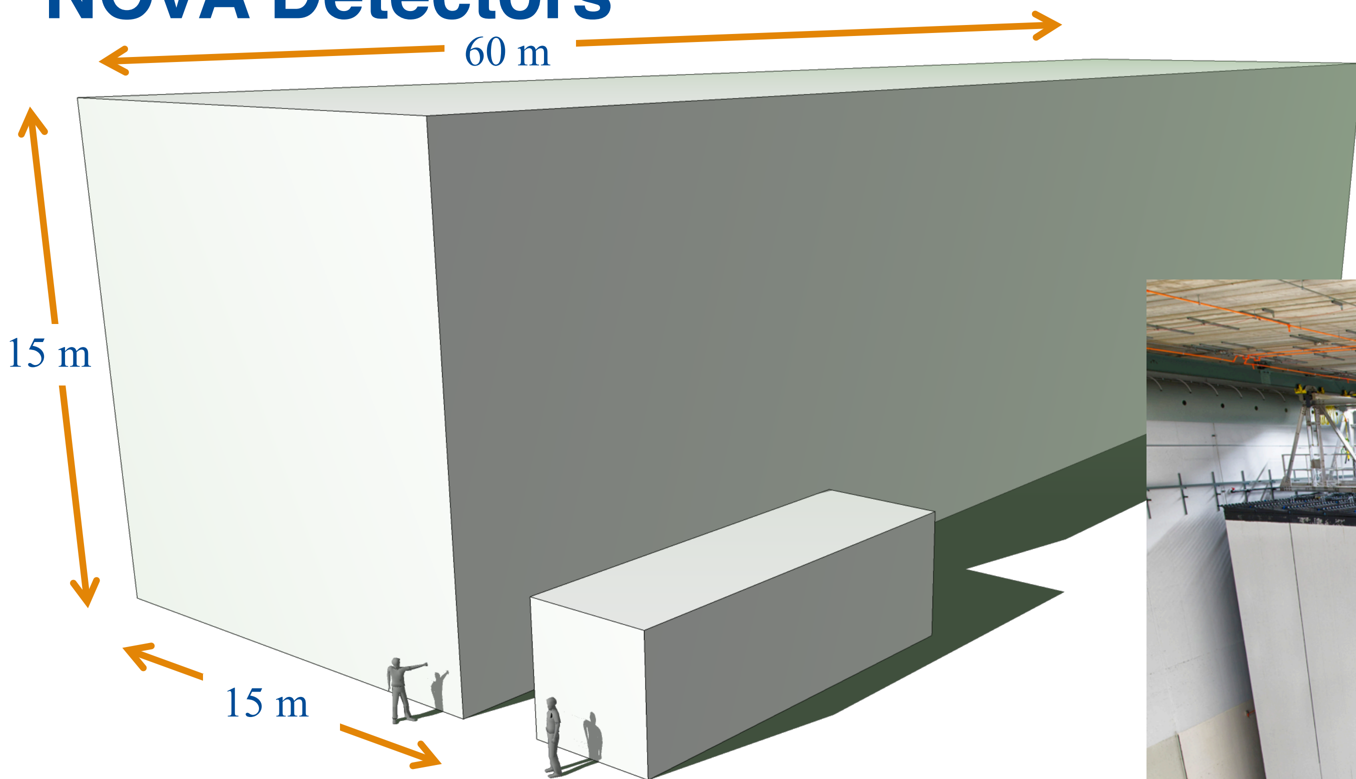
32 cells per Avalanche Photo Diode



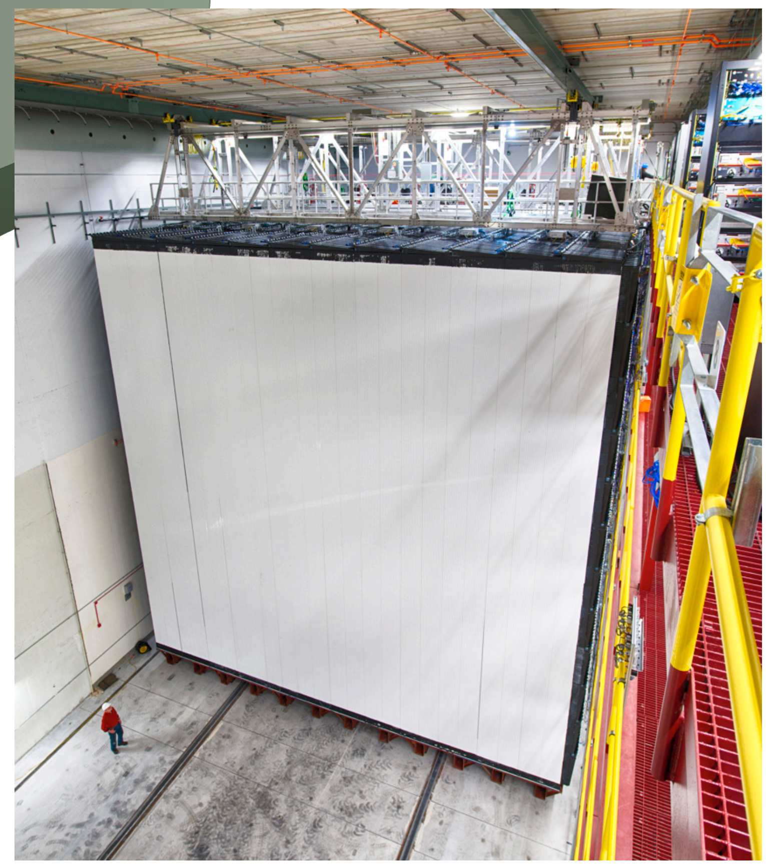
- ~6 planes per radiation length
  - Excellent Electro-magnetic shower characterization



NOvA Detectors

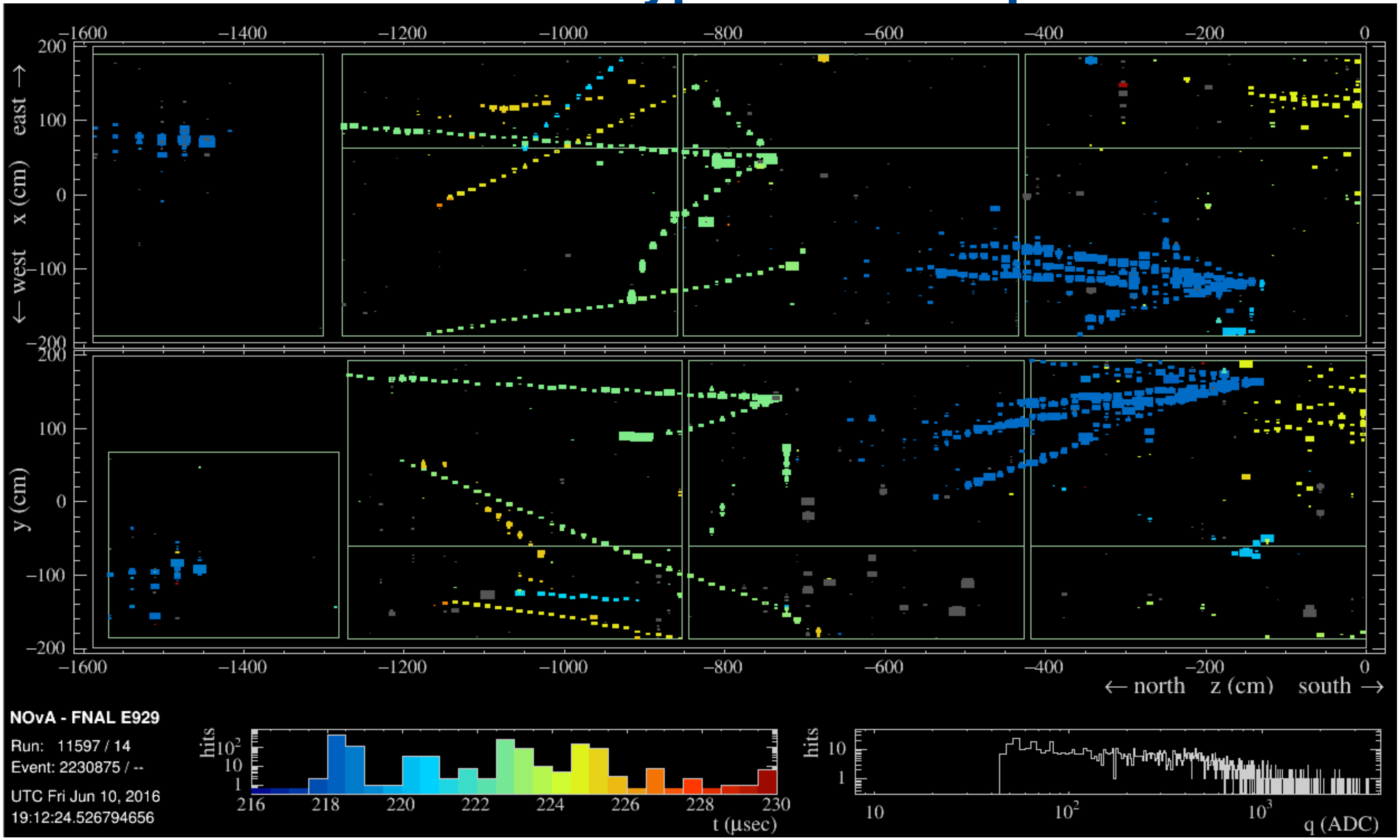


- Far Detector
  - 14 kT
  - 896 planes



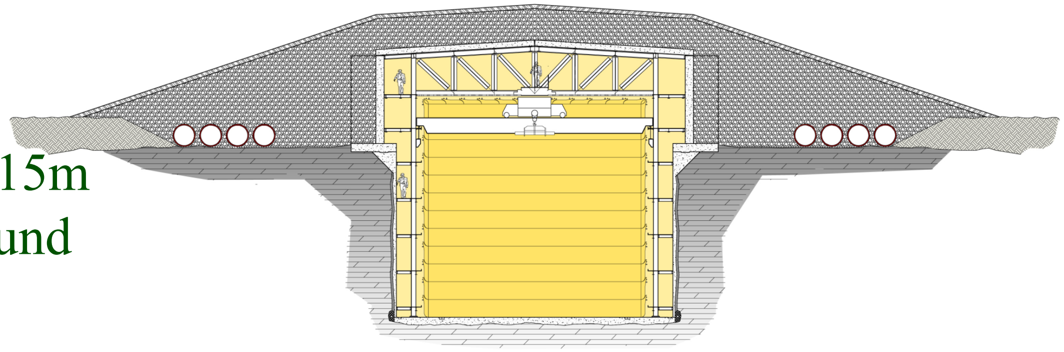
- Near Detector
  - 293 tons
  - 192 planes, plus a muon catcher with 10 planes of iron

NOvA Near Detector – Typical NuMI Spill

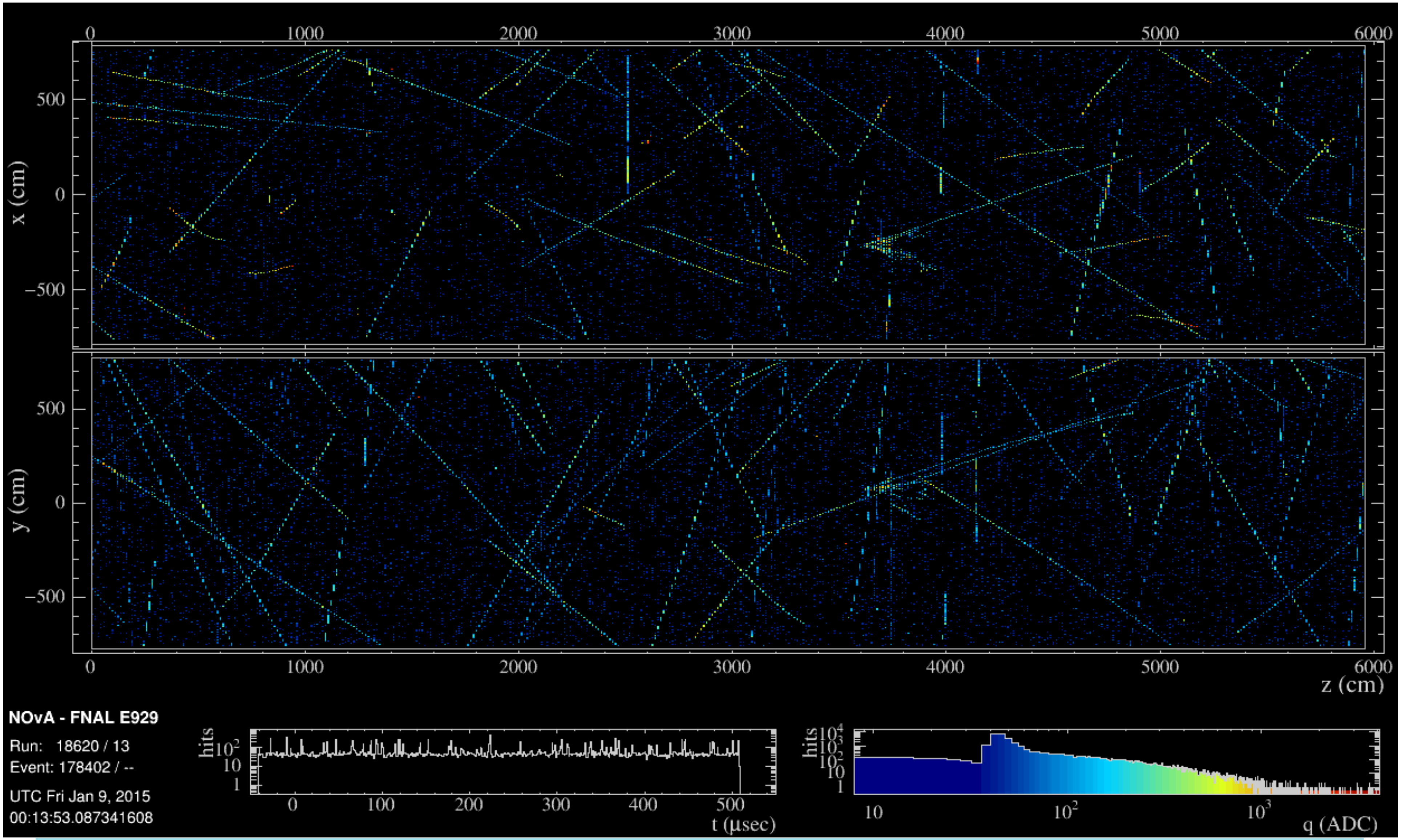


Far Detector

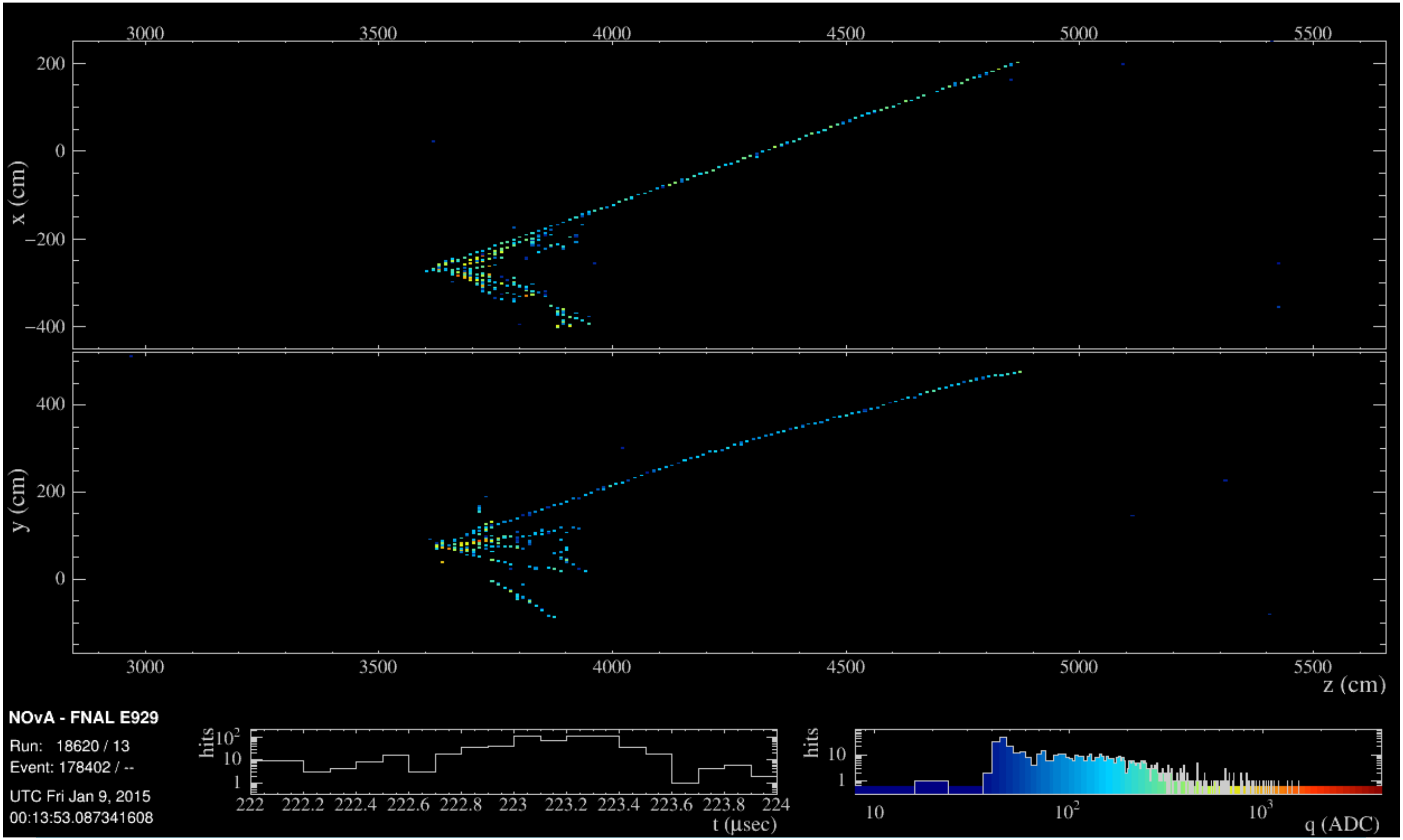
- Detector is mostly below grade
- Overburden: 1.37m concrete + 0.15m Barite ($BaSO_4$) for cosmic background reduction



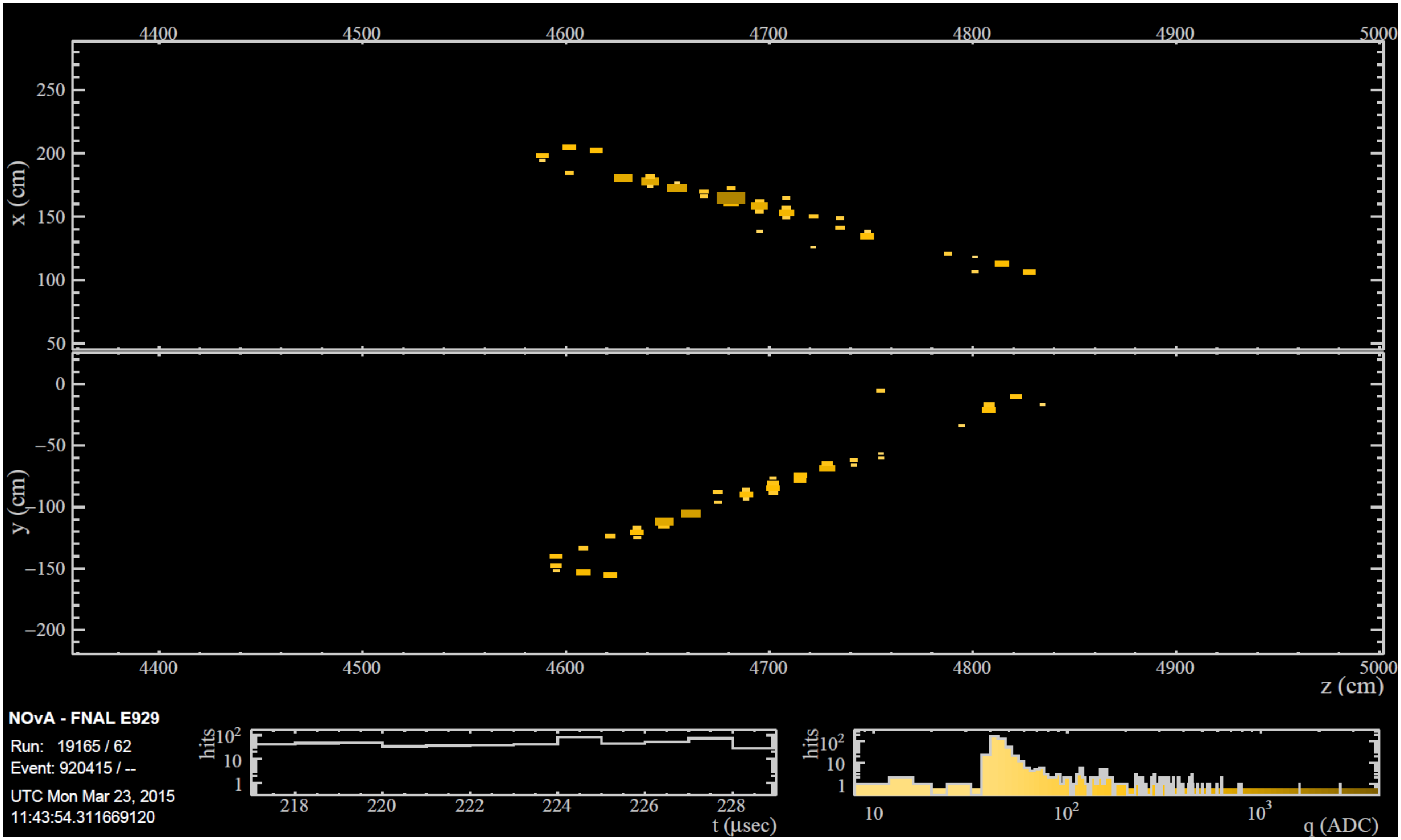
550 μs NOvA Far Detector Beam Trigger Window



Zoomed NOvA Far Detector Neutrino Event



1st Analysis Far Detector ν_e Candidate Event



Progress in the past year

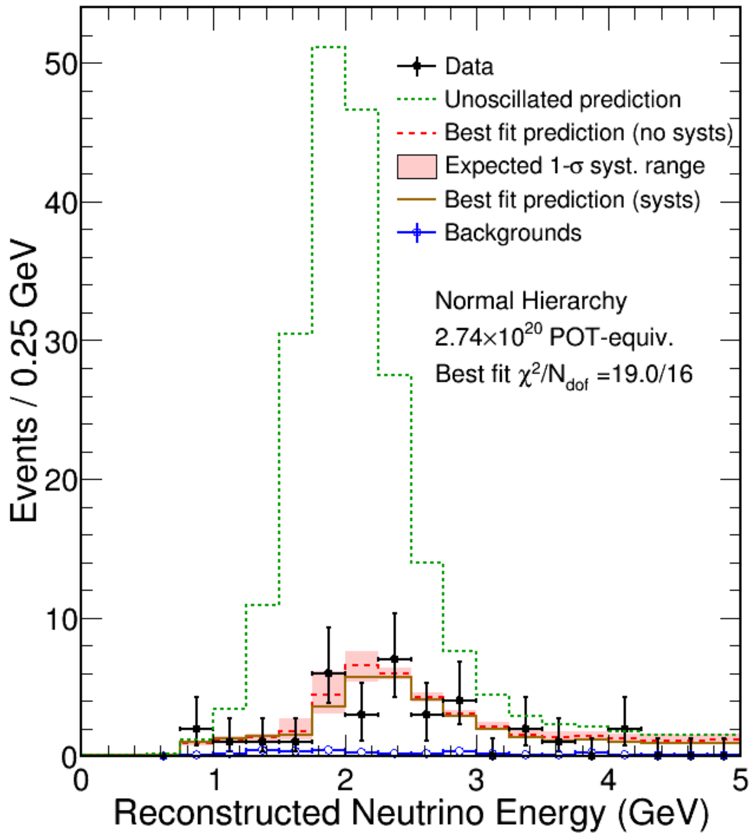
- First ν_e appearance and ν_μ disappearance results
  - Papers published this spring
- Continued to train future leaders in neutrino physics
  - 9 PhDs awarded in last year
  - 10 talks and posters at recent New Perspectives conference
- Higher beam power
- Better detector performance
  - Higher APD gain in Far Detector
  - Higher Far Detector uptime
- Improved data processing efficiency
- Preliminary ν_e cross section result
- Improvements to ν_e and ν_μ analyses
- Informal discussions with T2K on future cooperations

Degrees Award on NOvA Research

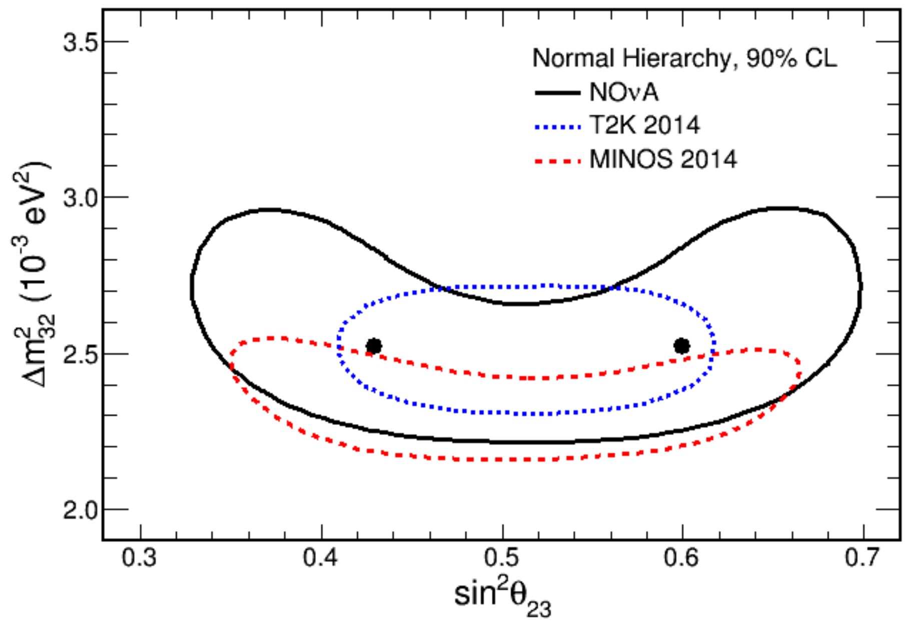
Lyudmila	Kolupaeva	6/30/15	MS	INR	Optimization of long baseline accelerator neutrino experiment sensitivity for measuring neutrino mass hierarchy
Dmitry	Rodkin	7/16/15	MS	INR	Estimation of the rate of nu_e signal and background events in NOvA experiment
Roman	Klokov	7/16/15	BS	JINR	Selection of quasi elastic neutrino scattering events in the near detector of NOvA experiment
Evan	Niner	8/10/15	PhD	UI	Observation of Electron Neutrino Appearance in the NuMI Beam with the NOvA Experiment
Eric	Flumerfelt	8/14/15	PhD	UTn	DAQ Software Contributions, Absolute Scale Energy Calibration and Background Evaluation for the NOvA Experiment at Fermilab
Kanika	Sachdev	8/31/15	PhD	UMn	Muon Neutrino To Electron Neutrino Oscillation in NOvA
Susan	Lein	9/1/15	PhD	UNn	Muon Neutrino Contained Disappearance in NOvA
Michael	Baird	9/30/15	PhD	IU	An Analysis of Muon Neutrino Disappearance from the NuMI Beam Using an Optimal Track Fitter
Marco	Del Tutto	10/27/15	Laur	SUR	Neutrino Beam Simulations and Data Checks for the NOvA Experiment
Zukai	Wang	12/1/15	PhD	UVa	Search for Magnetic Monopoles with the NOvA Far Detector
Dominic	Rocco	3/25/16	PhD	UMn	Muon Neutrino Disappearance in NOvA with a Deep Convolutional Neural Network Classifier
Nicholas	Raddatz	4/15/16	PhD	UMn	Measurement of Neutrino Disappearance with Non-Fiducial Interactions in the NOvA Experiment
Tian	Xin	4/15/16	PhD	ISU	Observing Muon Neutrino to Electron Neutrino Oscillations in the NOvA Experiment

Plus 2 MS, 2 PhD from before 2015

First ν_μ Disappearance Results



*Phys. Rev. D **93**, 051104 (R) 2016*



$$\Delta m^2_{23} = \left(2.52^{+0.20}_{-0.18}\right) \times 10^{-3} eV^2$$

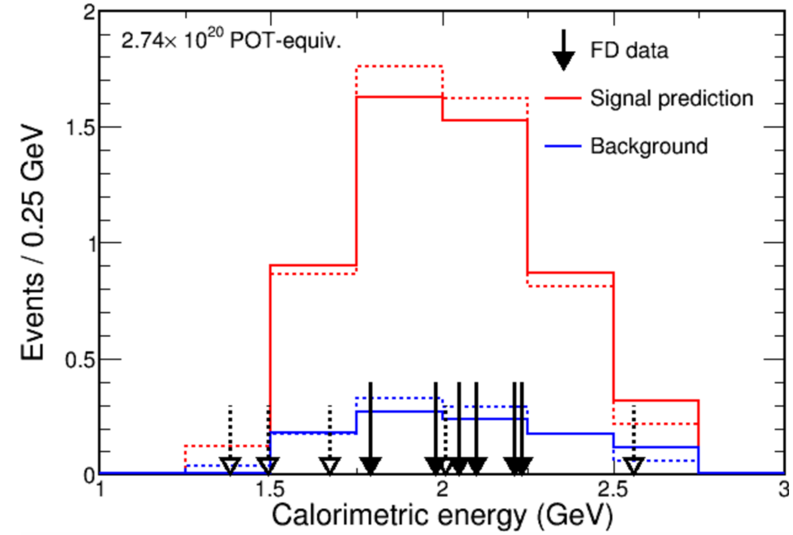
$$\sin^2(\theta_{23}) \in [0.38, 0.65]\ 68\% CL$$

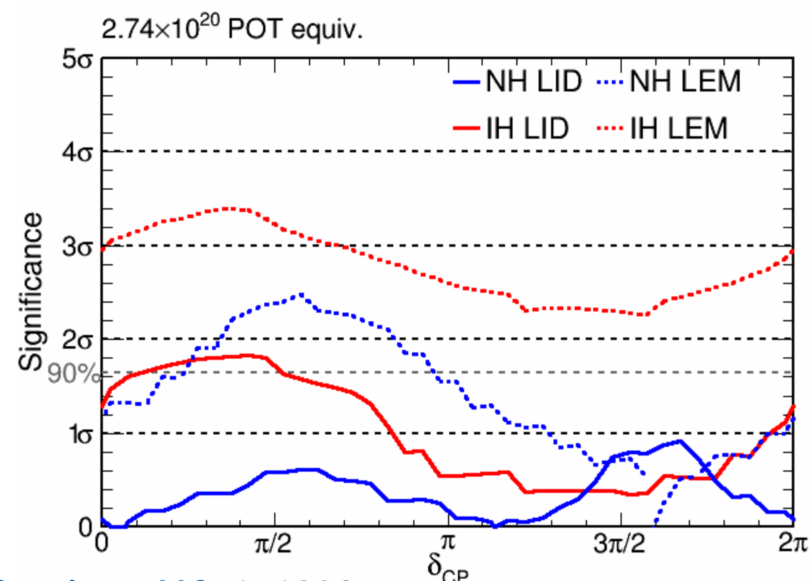
Values shown assuming Normal Hierarchy

- 33 ν_μ candidate events observed
  - On background of 3.4 events
  - 212 expected without oscillations

First ν_e appearance result

- Two ν_e CC event selectors
  - EM shower likelihood based – LID
  - Library Event Matching - LEM
  - Observe 6 LID, 11 LEM on BG of 1
    - 3.3 σ (LID), 5.3 σ (LEM)
  - All LID events are in LEM
    - 7.8% P-value for this combination given expected overlap
- Significance of NOvA result vs. Mass Hierarchy and δ_{CP}
  - Use reactor θ_{13} constraint
  - Marginalize over θ_{23}, other unknowns
  - Hint in favor of Normal Hierarchy and δ_{CP}~$3\pi/2$



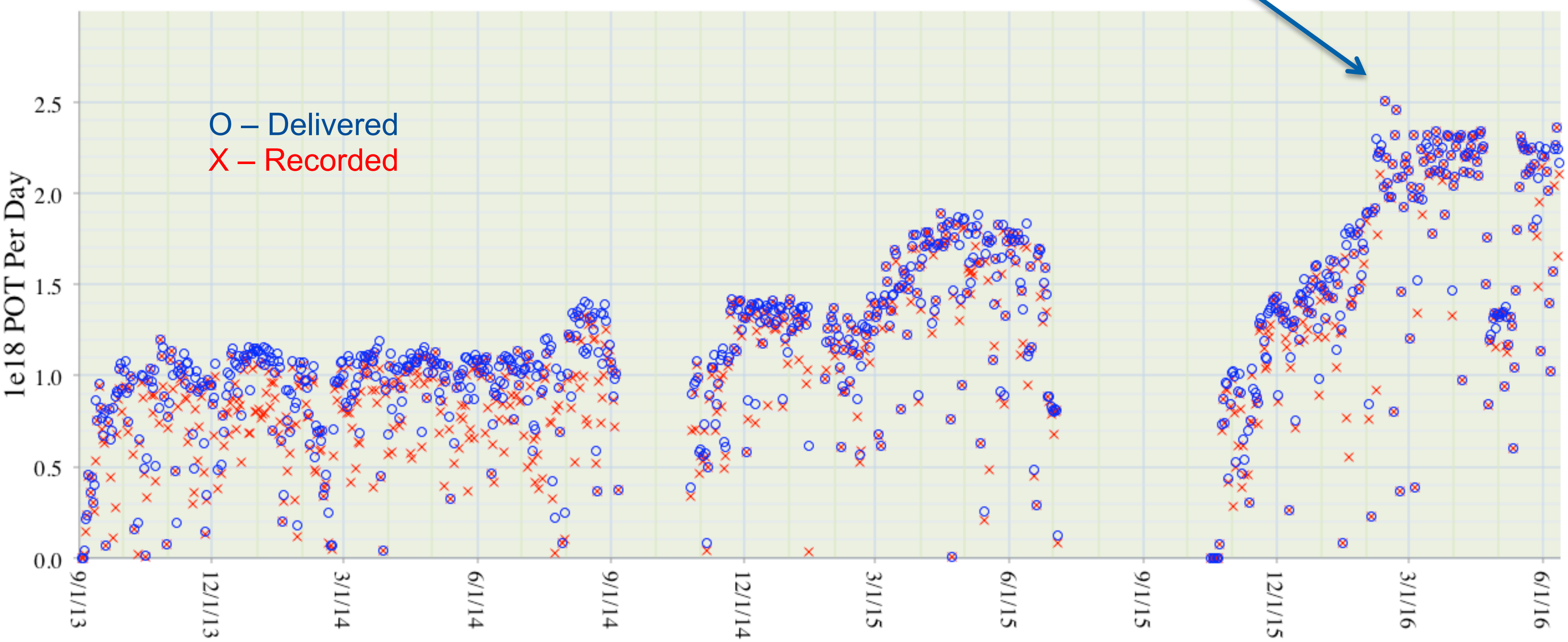


Phys. Rev. Lett. ***116****, 151806*

NOvA Far Detector Data Taking

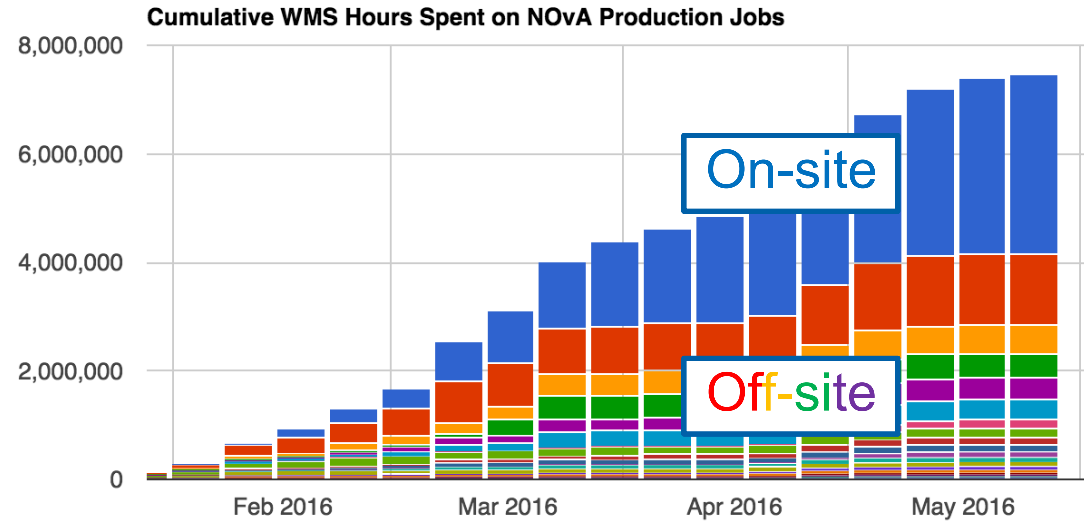
FY	Far Detector Beam-weighted Uptime
‘14	86% (Construction)
‘15	95.5%
‘16	96.3%

Uptime 98.3% since March 1, 2016 thanks to help from SCD DAQ experts
Coincident with AD achieving regular 520 kW NuMI operations

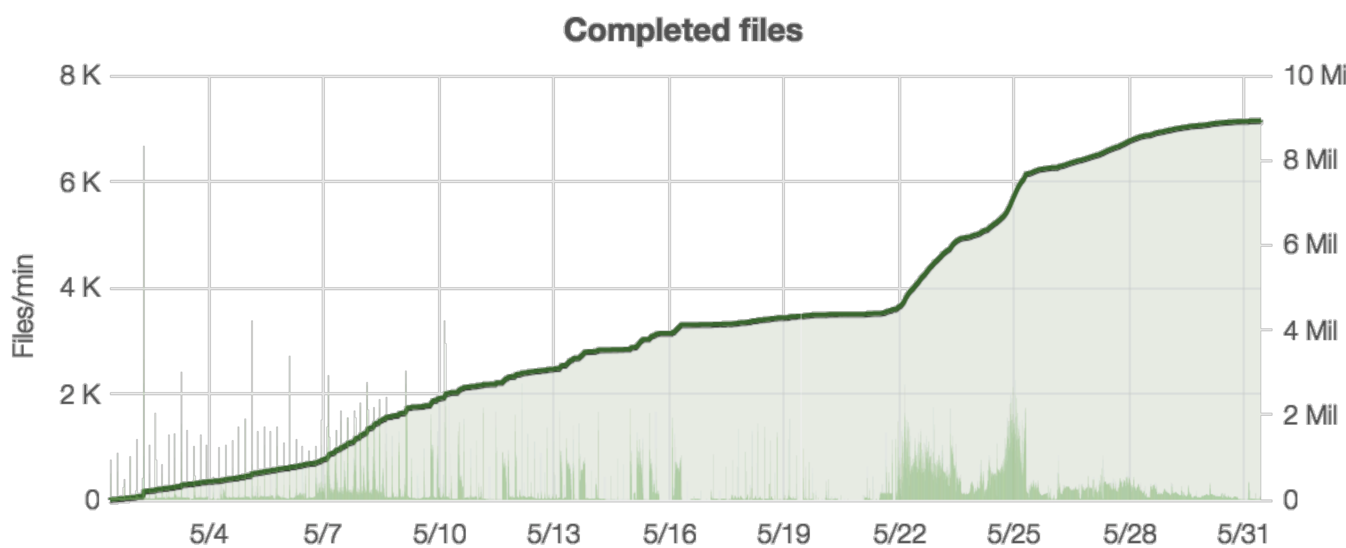


Offline Computing

- Improved efficiency of offline operations thanks to close collaboration of NOvA and Fermilab SCD
  - E.g., half of jobs run off-site thanks to FIFE technical support

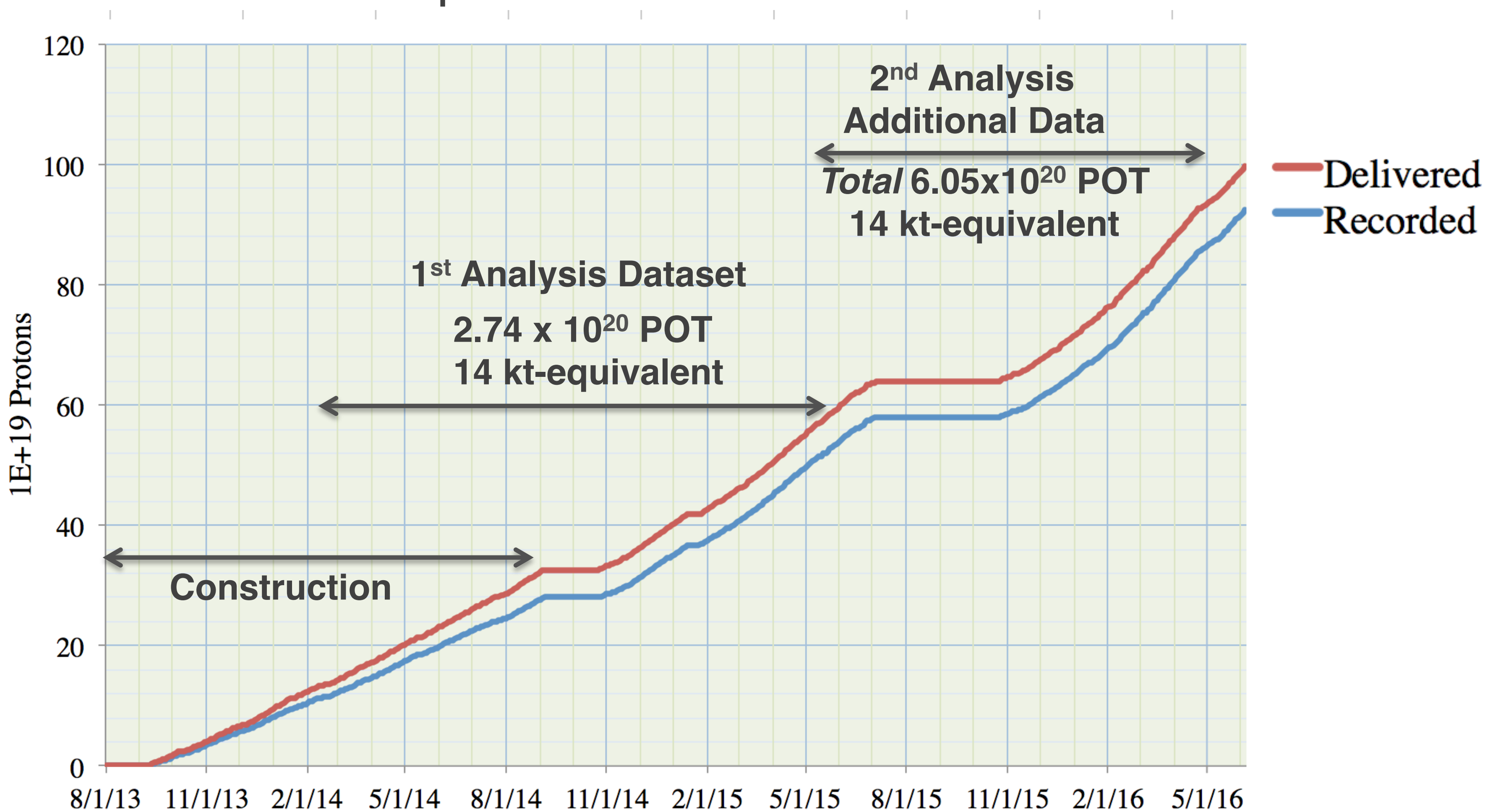


- Enormous data volume
  - 7 PB of data catalogued



NOvA Second Analyses

Far Detector exposure

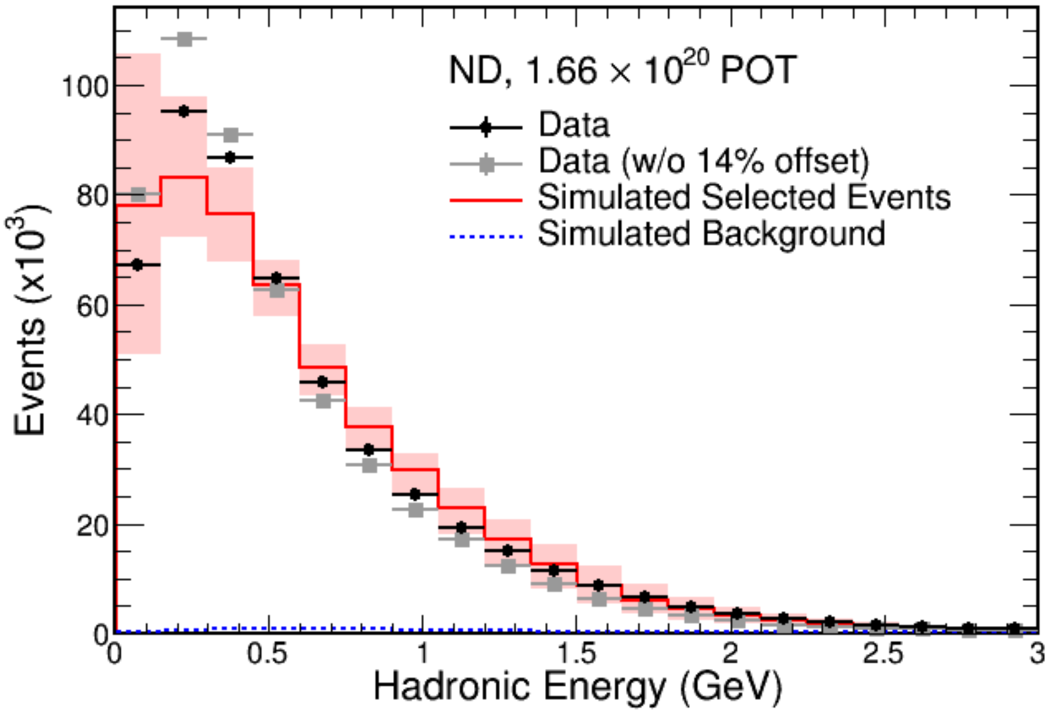


Upcoming Results – Neutrino 2016

- More than twice the exposure
  - 6.05×10^{20} POT (14-kt equivalent) vs. 2.74×10^{20} POT
- General improvements
  - Improved Hadronic Energy modeling
- Improvements to ν_e appearance
  - Improved ν_e CC identifier
  - Reoptimization of cuts for measurement
    - $\frac{s}{\sqrt{b}} \rightarrow \frac{s}{\sqrt{s+b}}$
  - Fit in energy and ID purity bins
- Sterile Neutrino Search
  - Neutral Current Disappearance in Far Detector

Hadronic Energy

- In first analyses, 14% discrepancy observed between data and MC hadronic energy scales
  - – 14% shift applied, with full shift taken as systematic uncertainty
- Largest source of systematic uncertainty on $\sin^2(\theta_{23})$, Δm^2

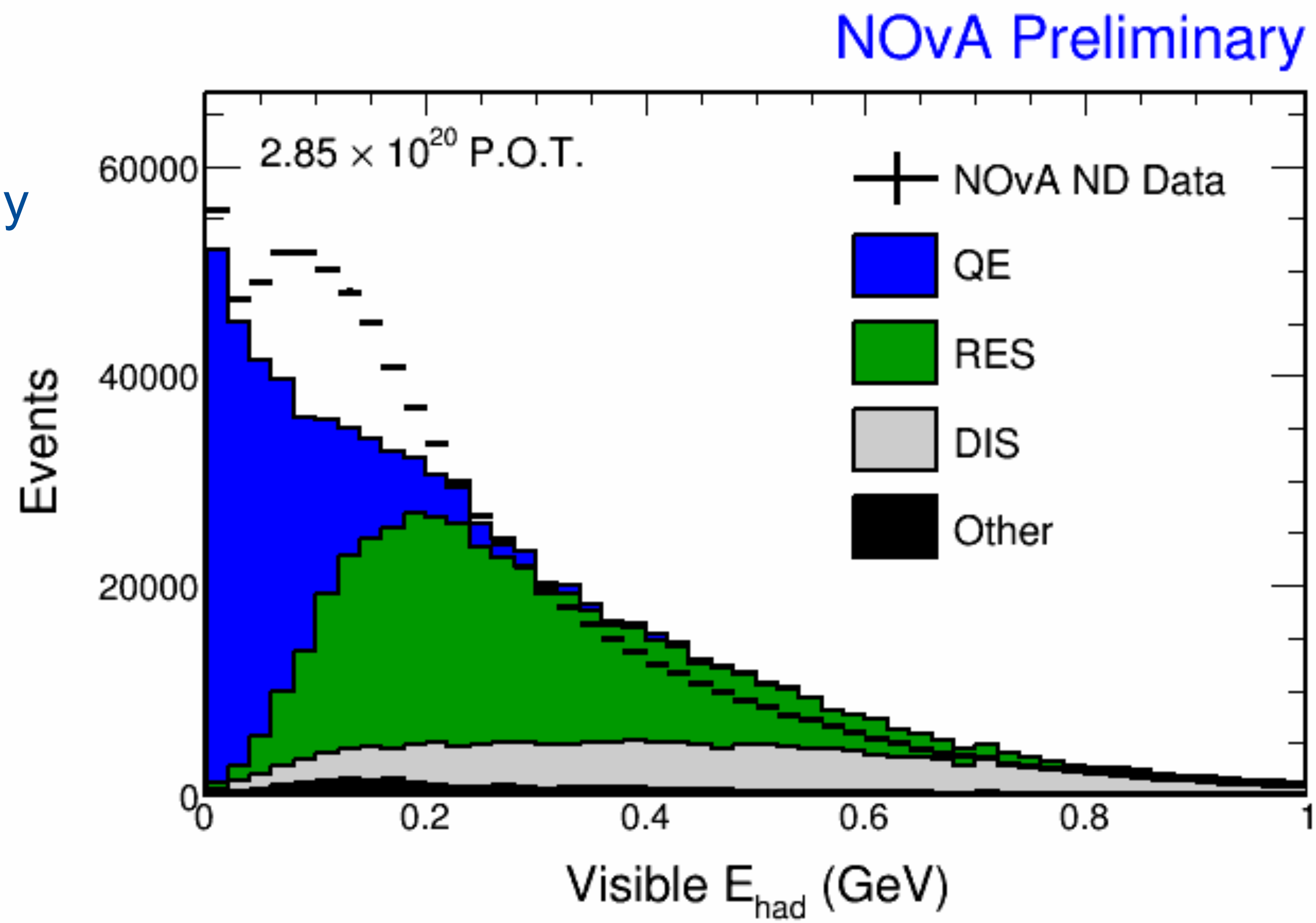


Source of uncertainty	%. Uncert. $\sin^2(2\theta_{23})$	%. Uncert. Δm^2_{23}
Absolute calorimetric energy calibration (14.9%)	4.1	2.6
Relative calorimetric energy calibration (5.2%)	3.4	0.6
Muon energy scale (2%)	2.2	0.8
Cross sections and final state interactions (15%–25%)	0.8	0.6
NC and ν_τ CC backgrounds (100%)	3.0	0.6
Particle-transport modeling	1.5	0.6
Beam flux (21%)	1.3	0.3
Normalization (1.4%)	0.4	0.2
Other oscillation parameters	1.8	2.2
Total systematic uncertainty	6.8	3.7
Statistical uncertainty	17.0	4.5

Original Hadronic Energy Modeling – First Analysis

Hadronic energy spectrum in selected ν_μ CC events

Comparison to GENIE 2.10.4



Improving Hadronic Energy Modeling

- Motivated by experience of MINERvA and other experiments, include multinucleon effects (2p2h) in simulation

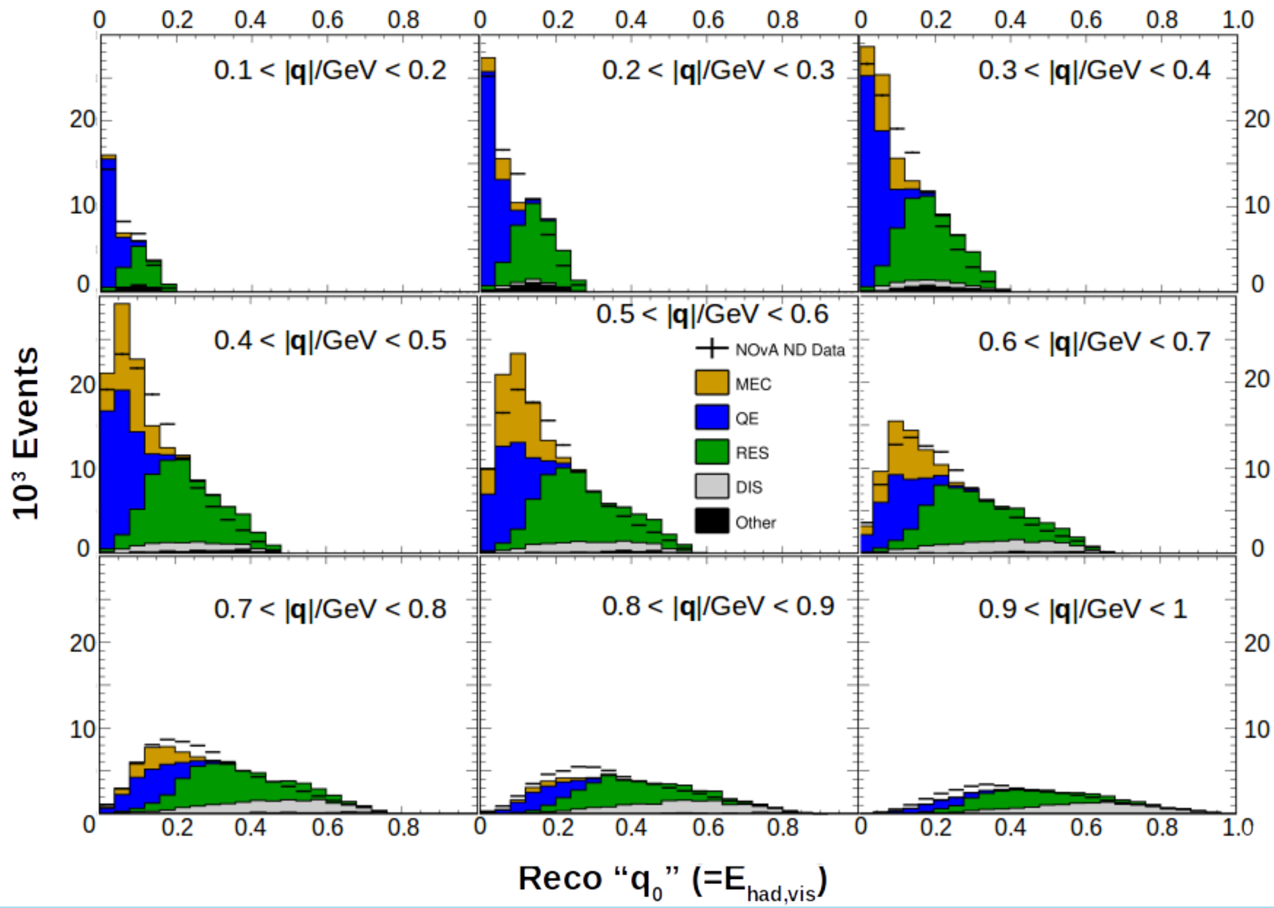
Use GENIE optional empirical Meson Exchange Current model

Tune to NOvA data in bins of |q|

Reduction of GENIE non-resonant π production also in line with MINERvA and others

Rodrigues, Wilkinson, McFarland arXiv:1601.01888

NOvA Preliminary



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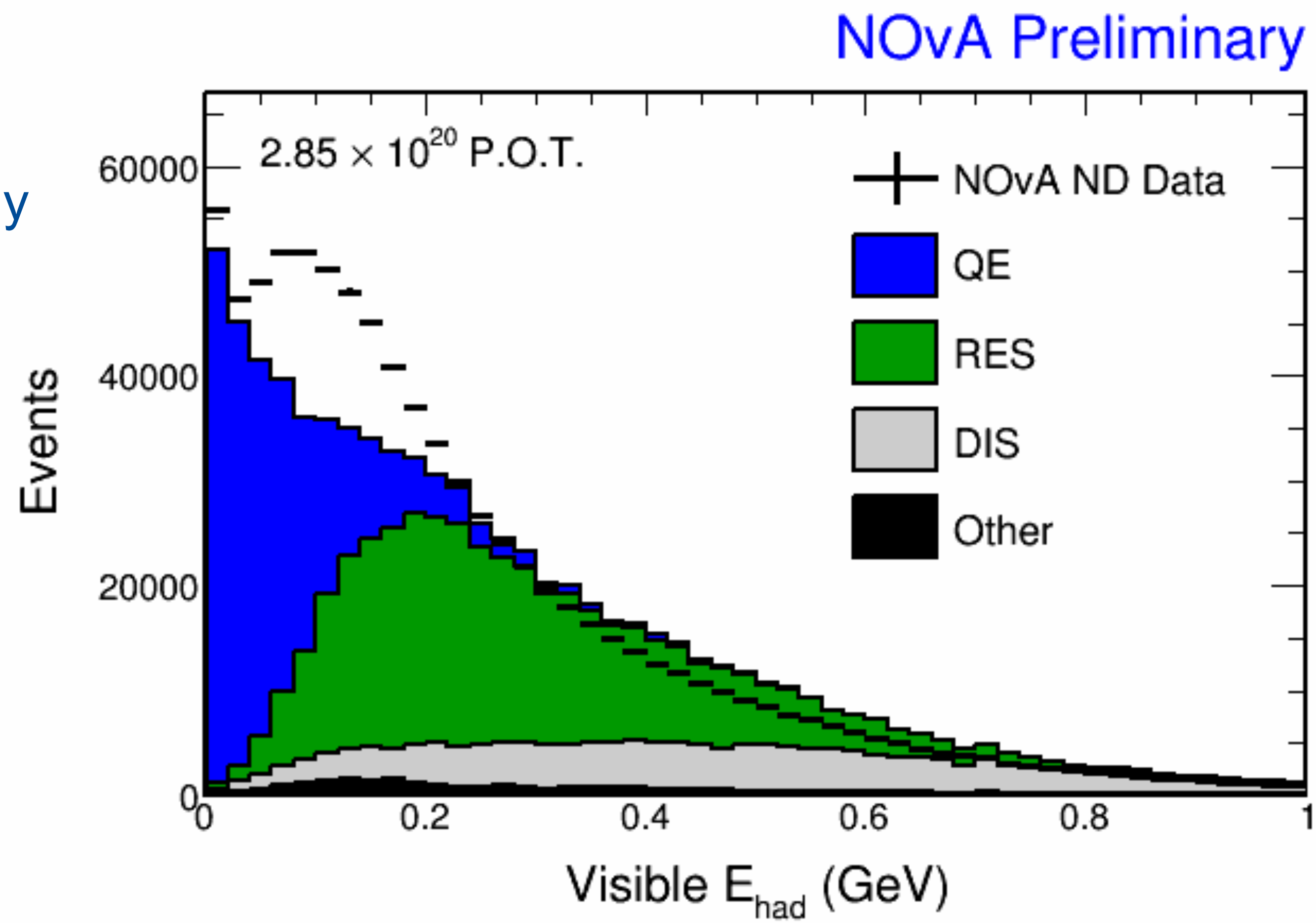
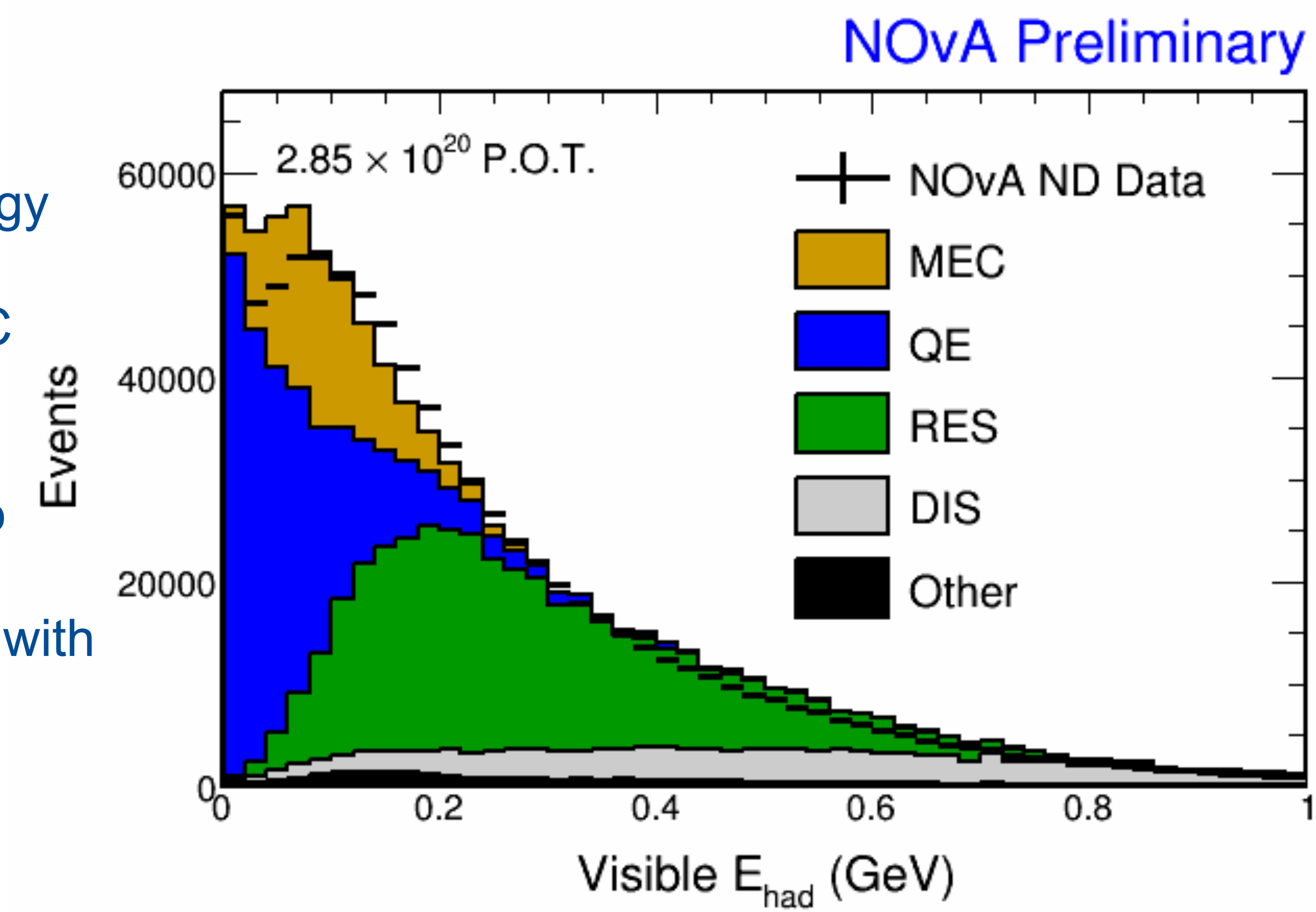


Improved Hadronic Energy Modeling

- Data-MC discrepancy is significantly reduced

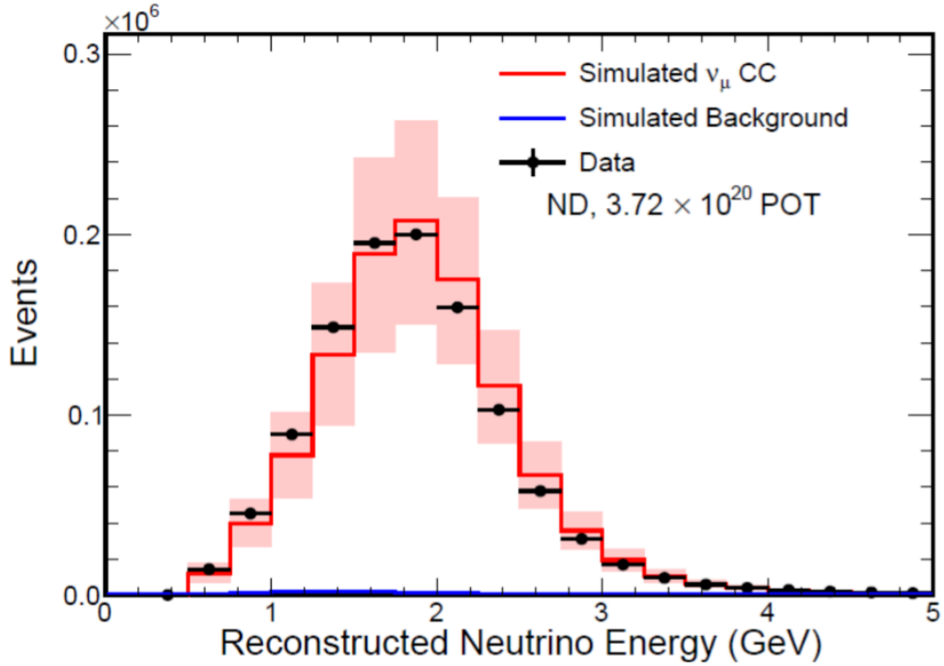
Hadronic energy spectrum in selected ν_μ CC events

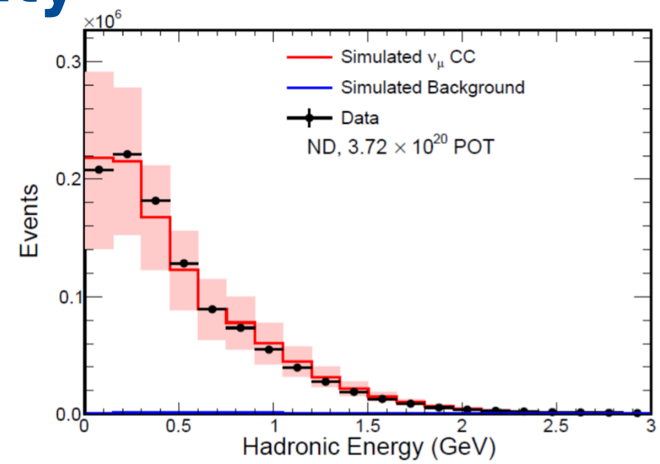
Comparison to tuned GENIE 2.10.4 with MEC model enabled



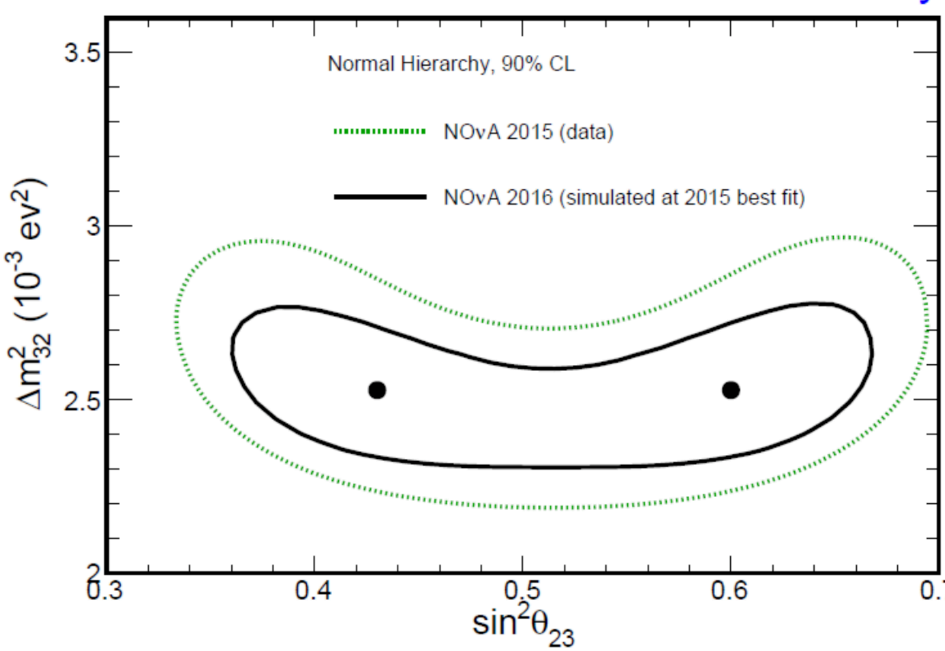
Second Analysis ν_μ CC Sensitivity

- Data-MC E_ν scale mismatched reduced from 5% to 2%



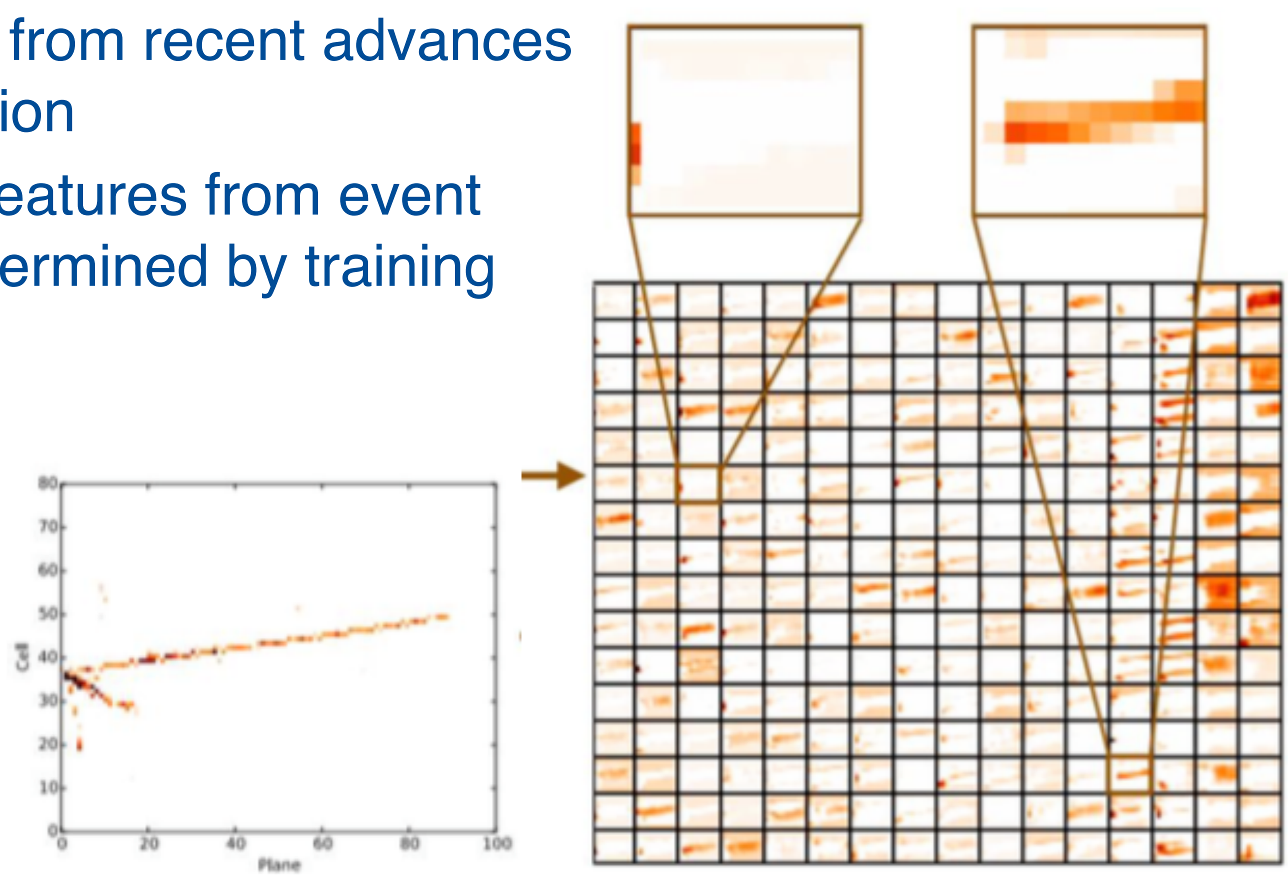


NOvA Preliminary



ν_e - Improved Event ID

- Convolutional Visual Network
  - Based on tools from recent advances in computer vision
  - Extract useful features from event using filters determined by training

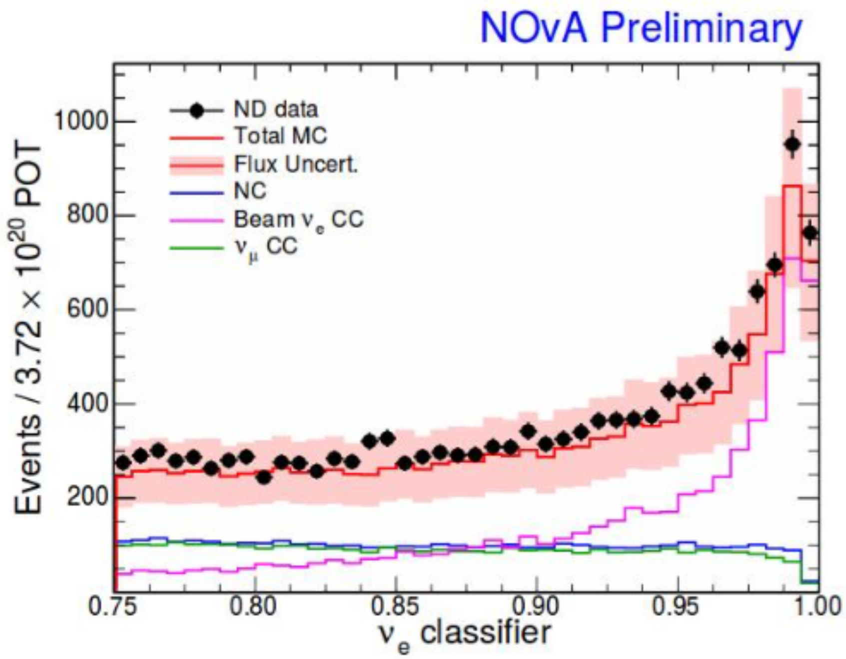


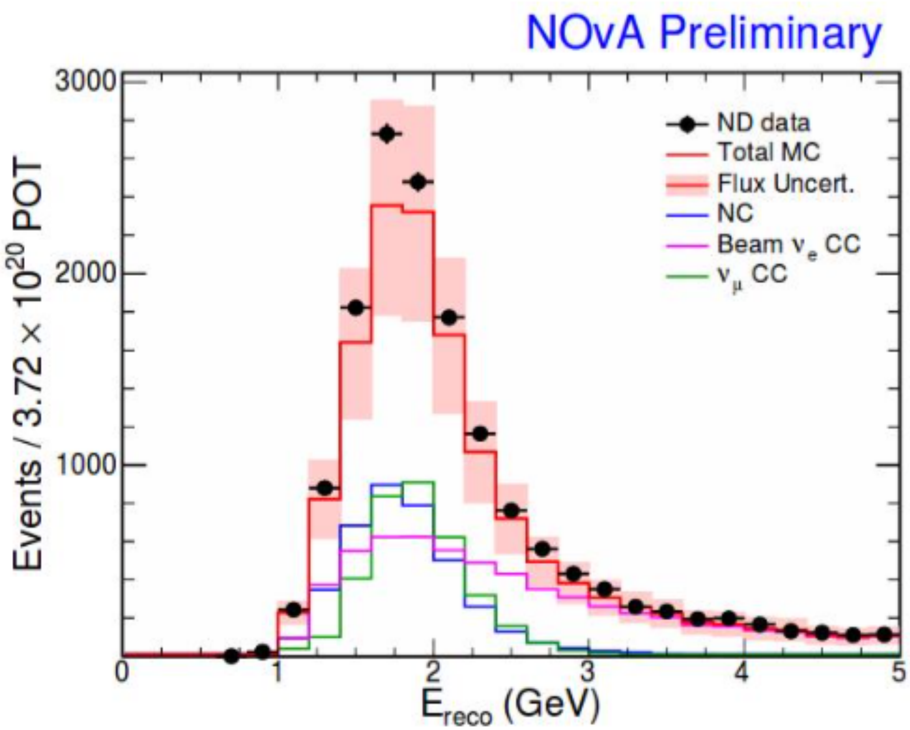
arXiv: 1604.01444 (submitted to JINST)

Feature map at
early convolutional layer

CVN Performance

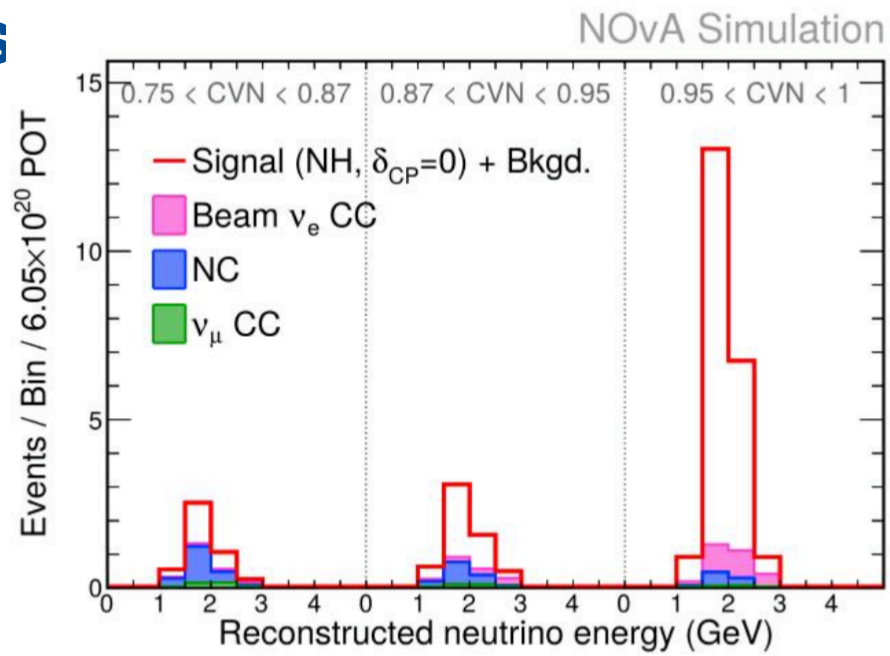
- For ν_e appearance, efficiency is 40% higher than IDs used in our first results, at similar purity

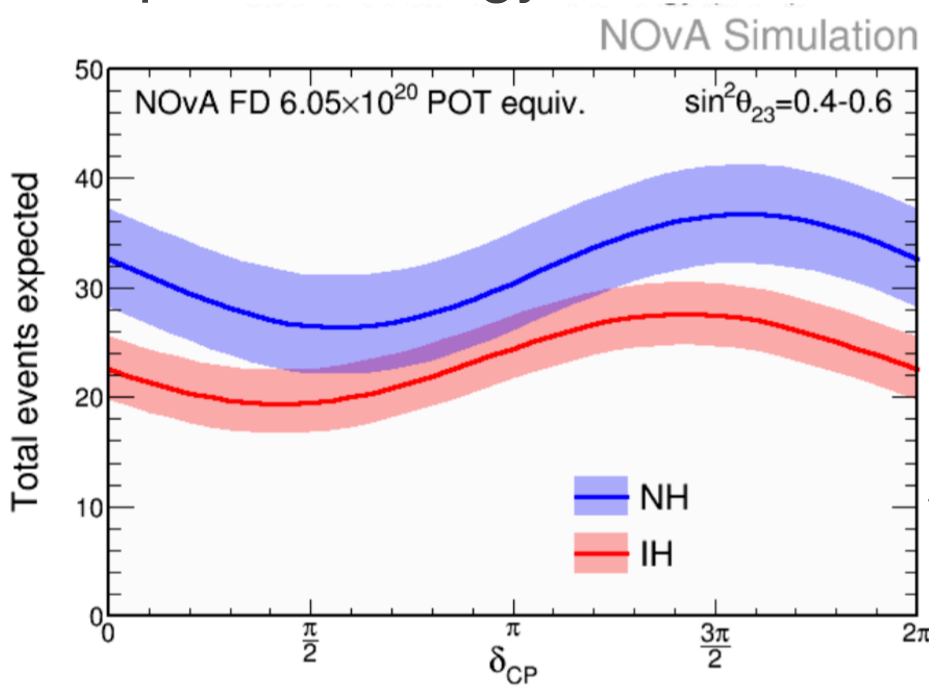




Additional ν_e Improvements

- Move from counting experiment to fit in bins of E_ν and CVN
- Improved of Near Detector for Far Detector Prediction
- Improved energy resolution





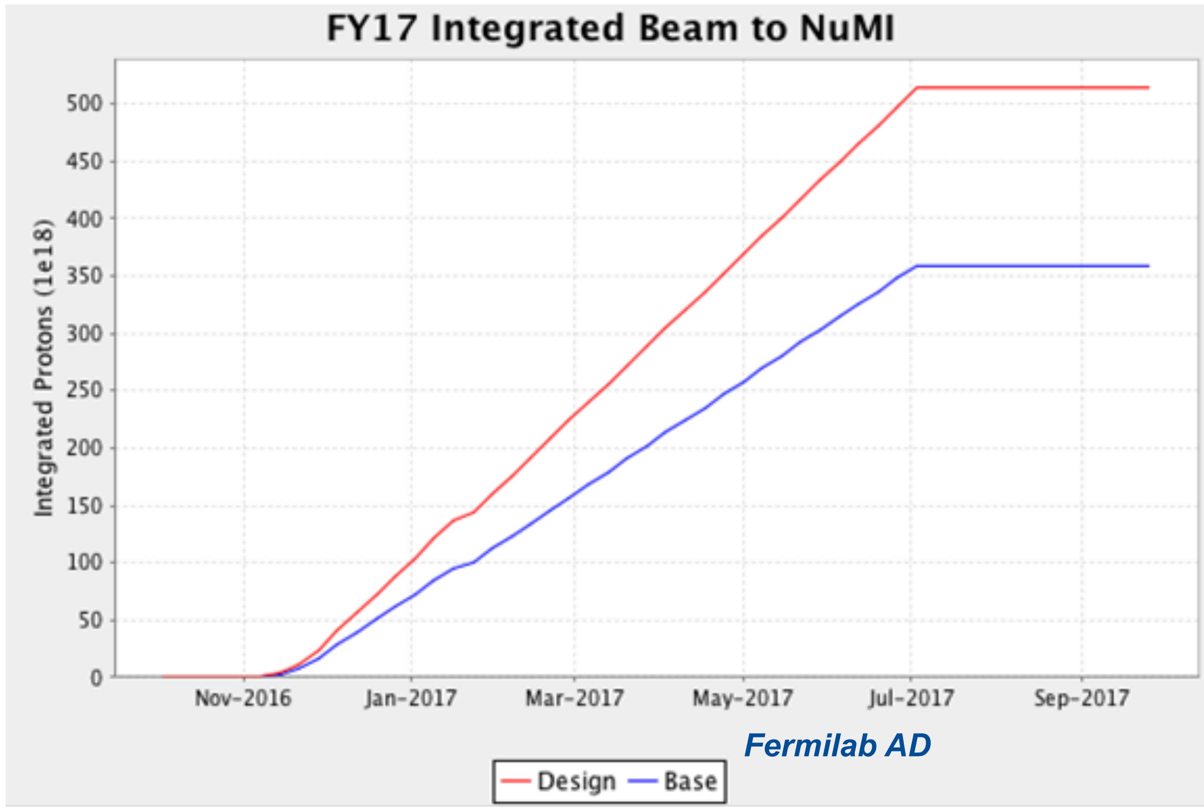
Far Detector Prediction vs. MH, δ_{CP}, $\sin^2(\theta_{23})$

T2K & NOvA - Possible Cooperation

- Meeting at Fermilab, March 2016
  - Informal discussions on opportunities for cooperation
  - T2K/NOvA collaboration spokespersons/analysis leaders
- Outcomes
  - In near term, the collaborations plan to explore possible further exchange/joint effort that could benefit neutrino interaction modeling and flux predictions
    - E.g., T2K has provided generous help to NOvA as we work on testing NEUT, T2K's neutrino interaction generator
  - Longer term, consider future joint analyses when each experiment's sensitivities warrants
    - ~5 year time scale
- Plan future joint meetings of T2K and NOvA personnel with wider participation in the coming year

FY17 Run Plan

- Projections
  - 7×10^{20} POT by end of FY16 (14-kt equivalent)
  - We expect to see 700 kW NuMI operation achieved by December 2016
  - Expect between 3.5×10^{20} and 5×10^{20} POT in FY17

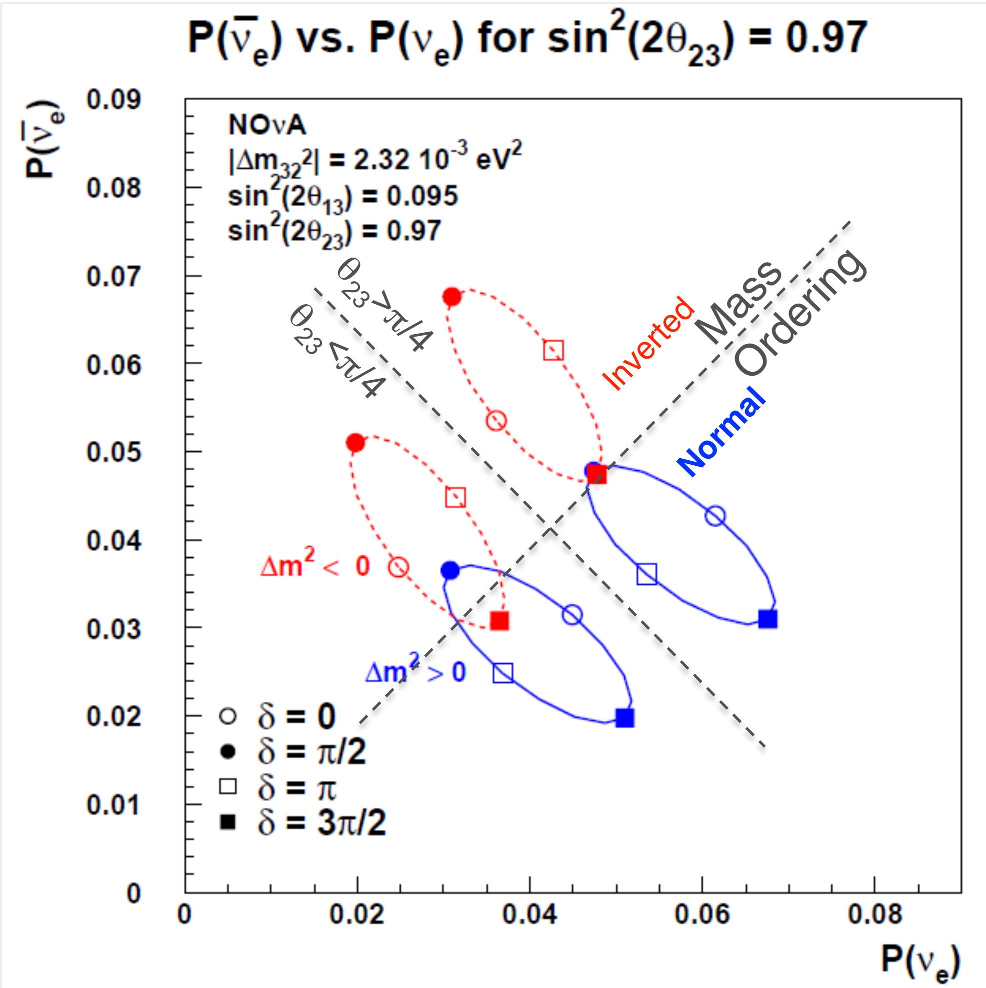


Anti-neutrino Running

- Prelude: we have requested a short run in anti-neutrino mode prior to the 2016 shutdown
  - Provide valuable lead-time in making any necessary adjustments to simulations and analysis
  - 4×10^{19} POT was approved by Program Planning

- We have always anticipated substantial anti-neutrino running over the course of the experiment
  - The optimization of the physics sensitivity is broad in $\nu/\bar{\nu}$ split
  - It is further broadened by uncertainty on θ_{23}

Appearance Probabilities



Mass Ordering

-Matter (MSW) effect due to presence of electrons in matter

-~20% effect for NOvA, 11% for T2K

CP Violation

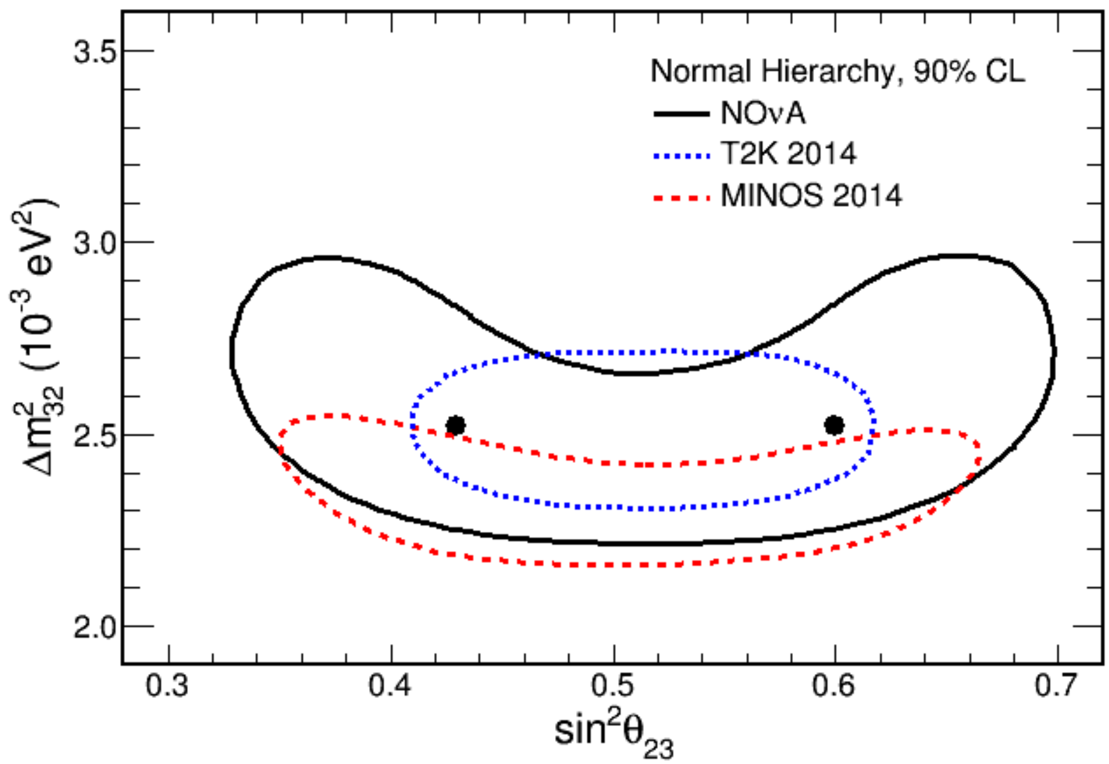
-Probabilities vary on ellipse according to δ_{CP}

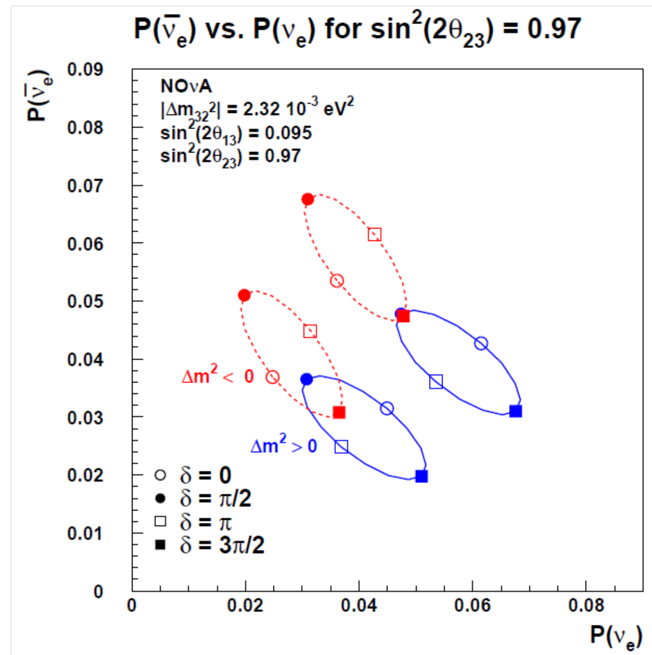
-~20% effect for NOvA

θ_{23} Octant from $\sin^2(\theta_{23})$ in leading term of $P(\nu_\mu \rightarrow \nu_e)$, $P(\nu_\mu \rightarrow \nu_e)$

-up to ~20% effect

Reminder – Current state of θ_{23}





FY17 Plan

- We would like to take $2x10^{20}$ POT in neutrino mode at the start of FY17 run
  - NuMI target will be replaced during shutdown, and the old/new target comparison will be important.

- This will give us $9x10^{20}$ POT 14 kt-equivalent in neutrino mode, which is half of our baseline neutrino run plan

- After the $2x10^{20}$ POT, switch to anti-neutrino running for the remainder of FY17

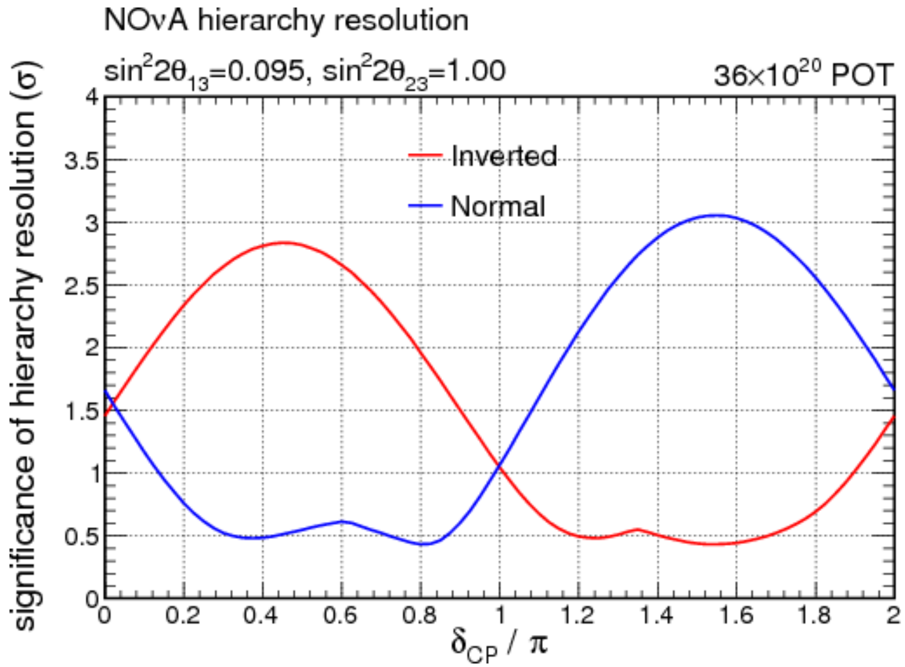
Summary

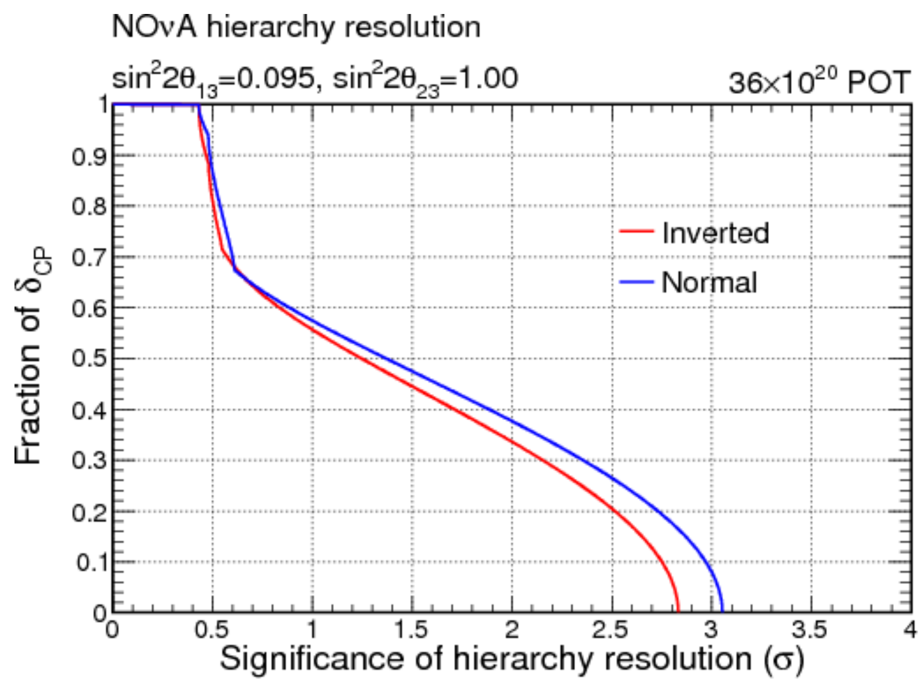
- NOvA has produced its first oscillation publications

- Updated analyses with more data will be presented at Neutrino 2016 in July

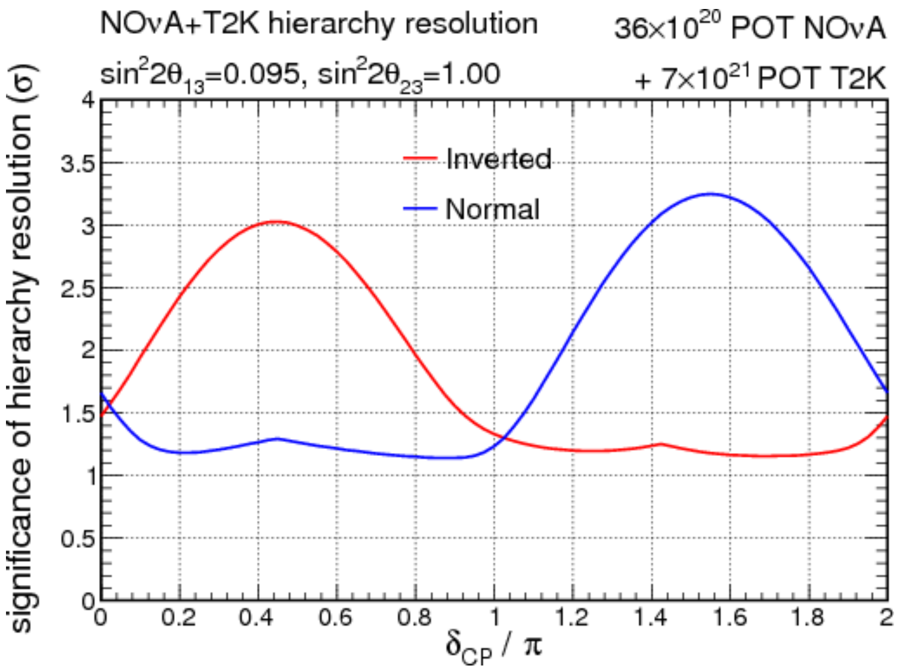
- We would like to switch to anti-neutrino after an additional 2×10^{20} POT in FY17

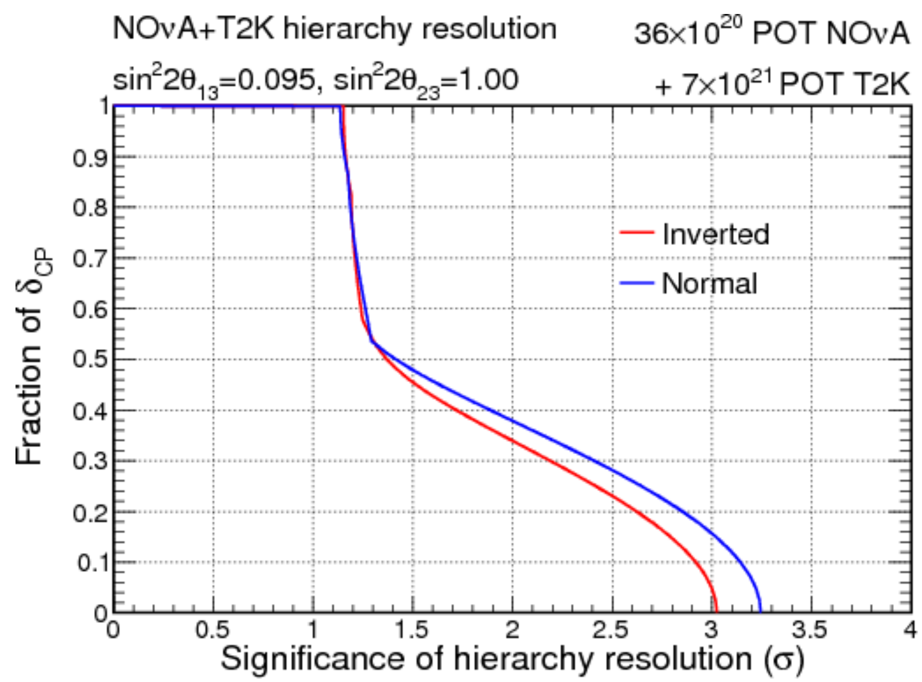
Sensitivities: Mass Hierarchy – NOvA



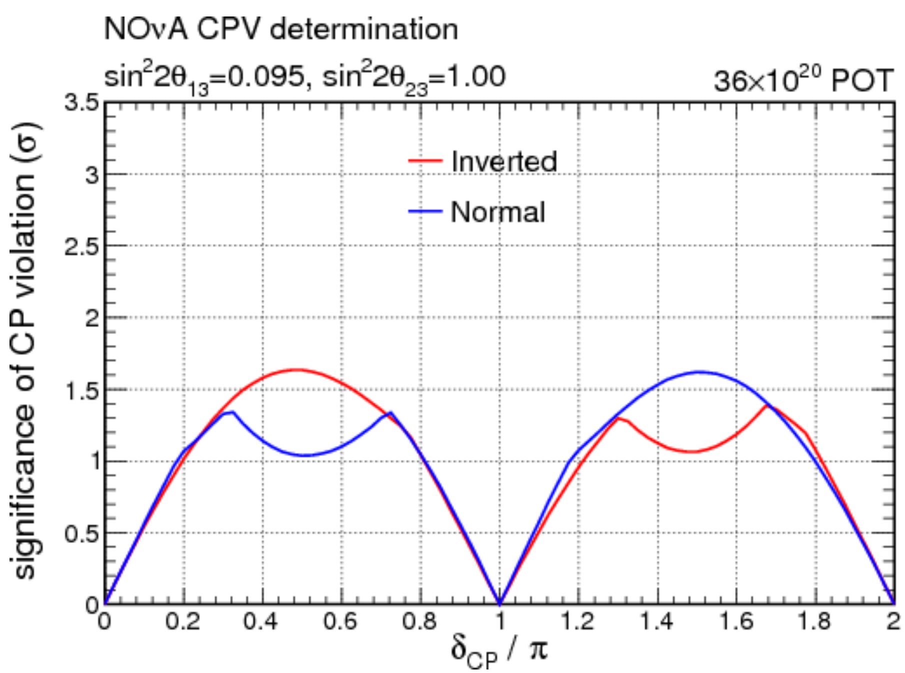


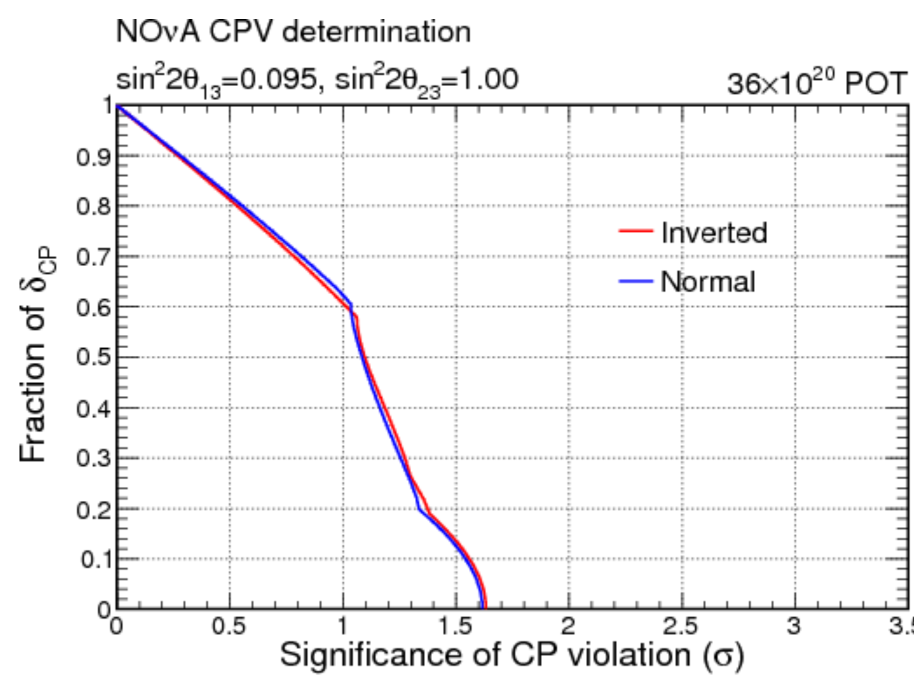
Sensitivities: Mass Hierarchy – NOvA+T2K



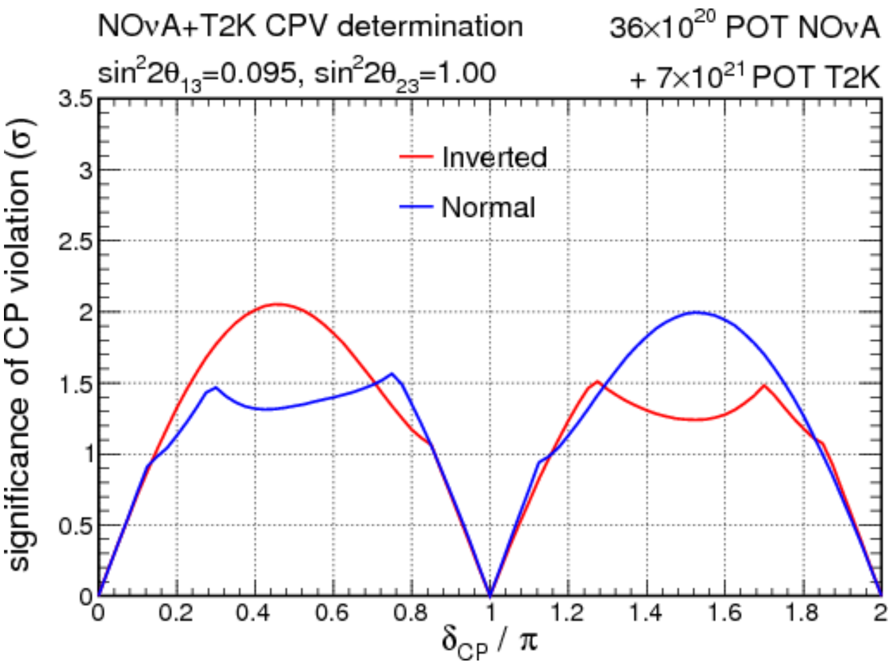


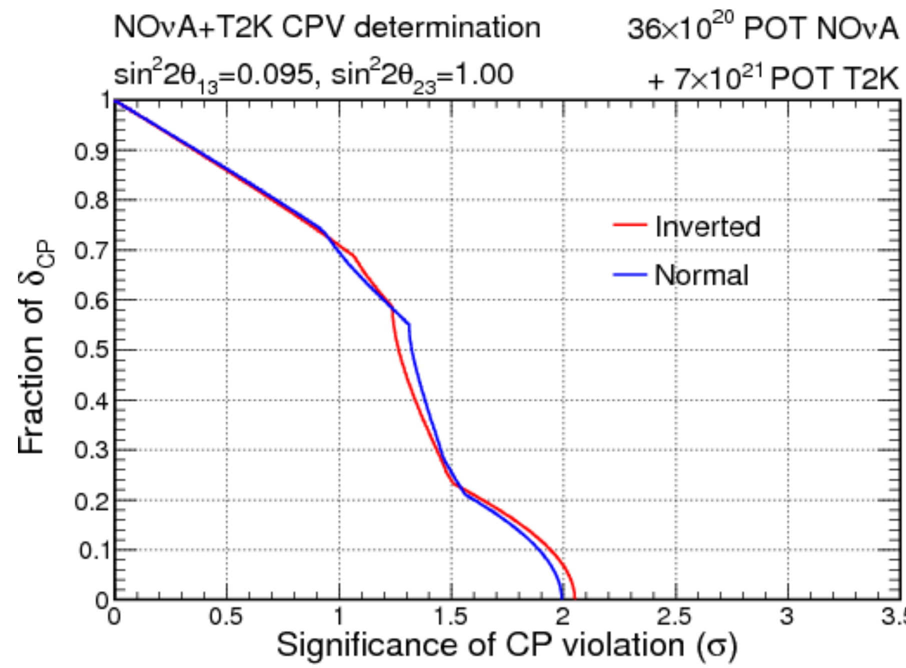
Sensitivities: CP Violation – NOvA





Sensitivities: CP Violation – NOvA+T2K

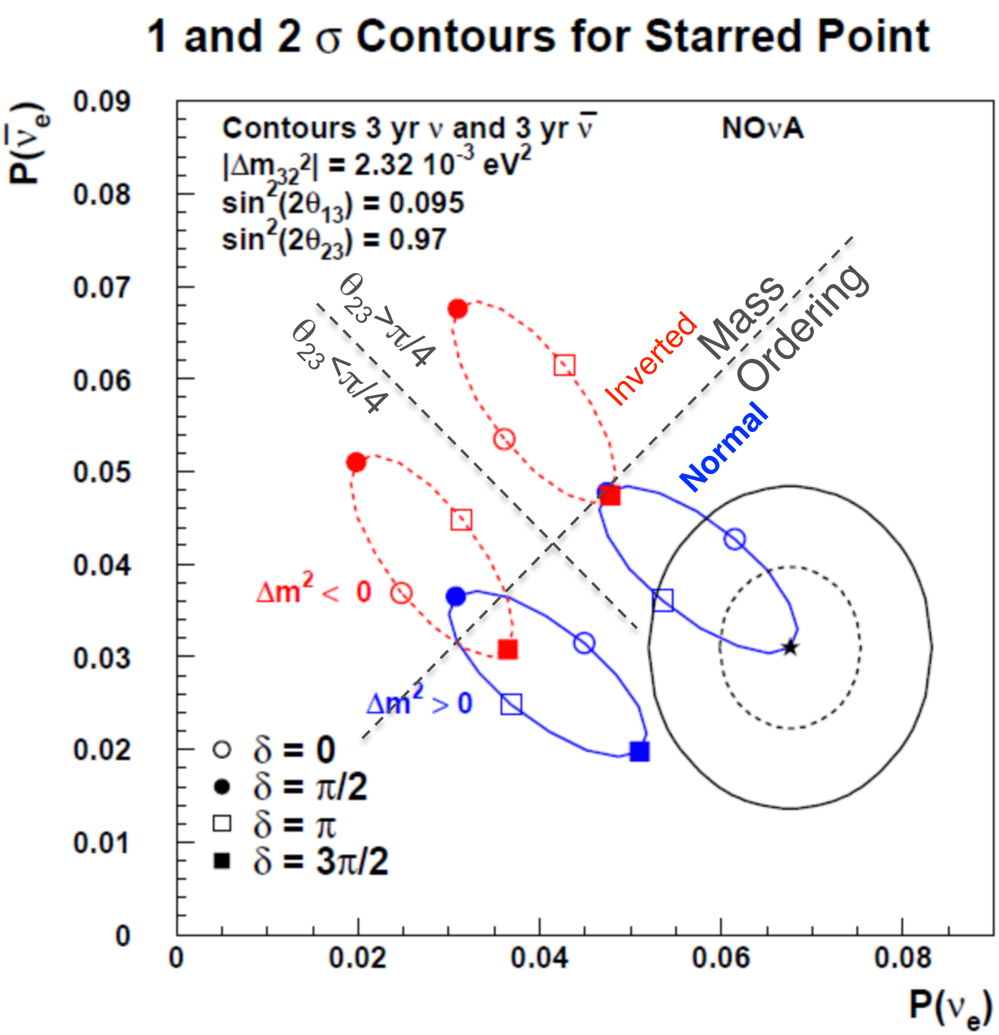




Near Detector Cross-section Measurements

- ν_e CC inclusive
- NC coherent π^0
- ν-e scattering
- ν_μ CC inclusive
- ν_μ CC 0-π
- ν_μ CC 2p2h
- ν_μ CC $\pi^{+/-/0}$
- Etc, and in anti-neutrinos

Long Baseline $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$



Mass Ordering

-Matter (MSW) effect due to presence of electrons in matter

-~30% effect for NOνA, 11% for T2K

CP Violation

-Probabilities vary on ellipse according to δ_{CP}

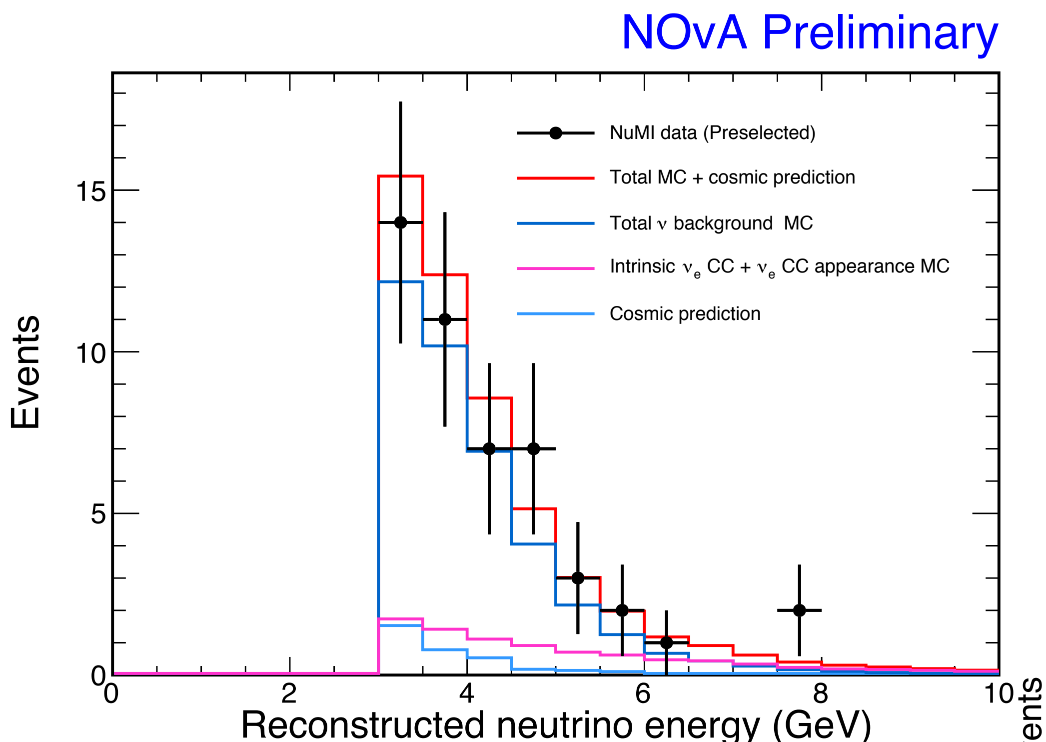
θ_{23} Octant from $\sin^2(\theta_{23})$ in leading term of $P(\nu_\mu \rightarrow \nu_e)$, $P(\nu_\mu \rightarrow \nu_e)$

Hypothetical measurement corresponding to most favorable parameter values.

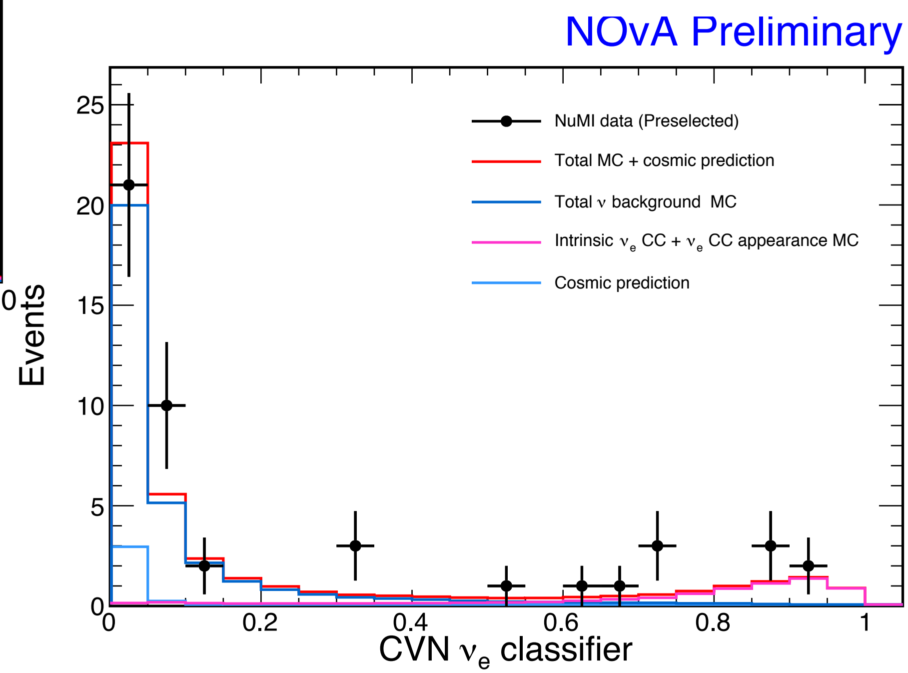
- 36×10^{20} Protons-on-target

Equal neutrino/anti-neutrino split

Pre-box opening check – High Energy Sideband

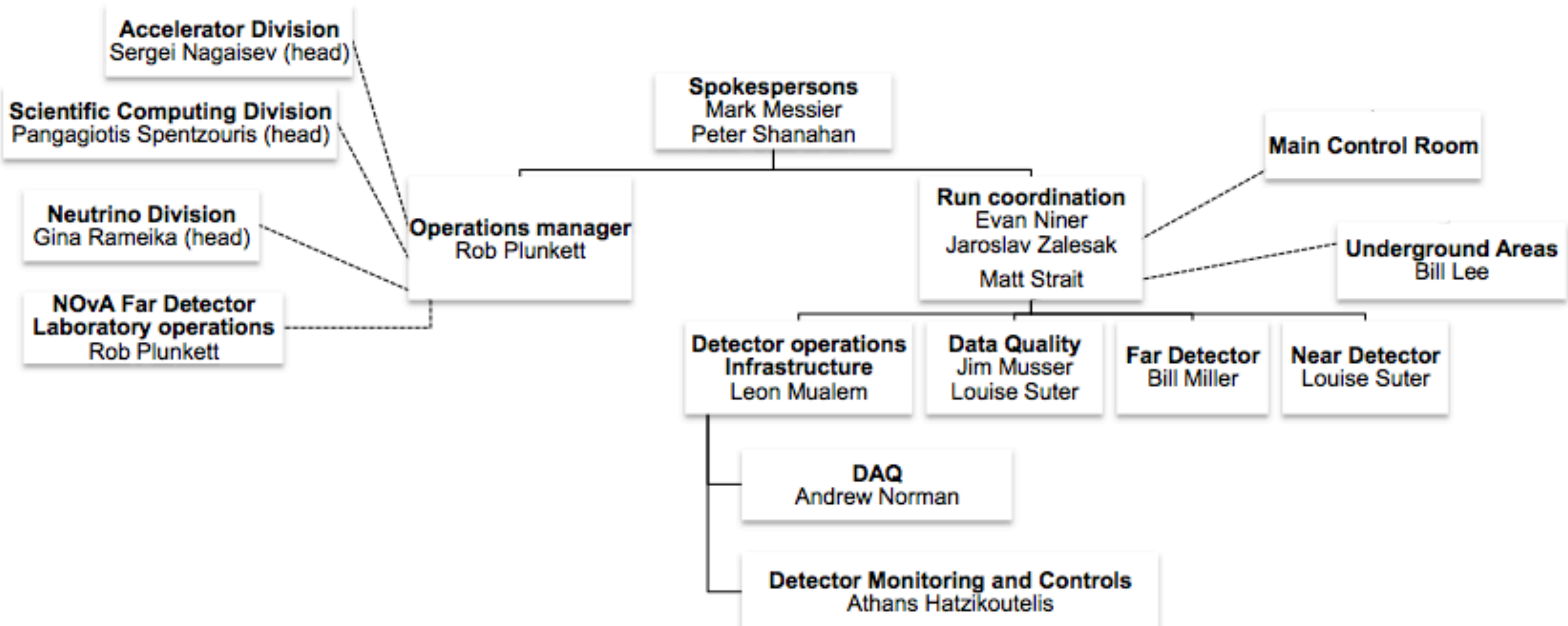


Far Detector events in HE Sideband passing pre-selection



Good Data-MC agreement in E_ν and CVN

NOvA Operations



Fermilab

Organization

- **Institutional Board** Tricia Vahle (chair)
- **Executive Committee**
- **Spokespeople** Mark Messier, Peter Shanahan
  - **Detector Operations** Evan Niner, Jaroslav Zalesak, Matt Strait, Rob Plunkett
  - **Data Driven Triggers** Norm Buchanan, Andrew Norman
  - **Calibration and alignment** Ryan Nichol, Keith Matera
  - **Computing** Alex Himmel, Andrew Norman (CS Liason)
    - **Software releases and production** Bruno Zamorano
      - **Release manager** Paul Sail
    - **Database coordinator** Jon Paley
  - **Physics analysis coordinator** Ryan Patterson, Mayly Sanchez
    - **Beam data and simulation** Alexander Radovic, Raphael Schroeter, Bob Zwaska
    - **Detector simulation** Adam Aurisano, Jim Musser
    - **Reconstruction** Chris Backhouse
    - **nue CC** Chris Backhouse, Tricia Vahle
    - **numu CC** Jeff Hartnell, Greg Pawloski
    - **NC/Sterile** Alex Sousa, Louise Suter
    - **ND physics** Mat Muether, Jon Paley
    - **Exotics** Craig Dukes, AlecHabig